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Workshop on the Advanced Design of Spoke Resonators Proceedings

Los Alamos
NATIONAL LABORATORY

LA-14005-C
Conference
Issued: January 2003

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Compiled by
Frank L. Krawczyk

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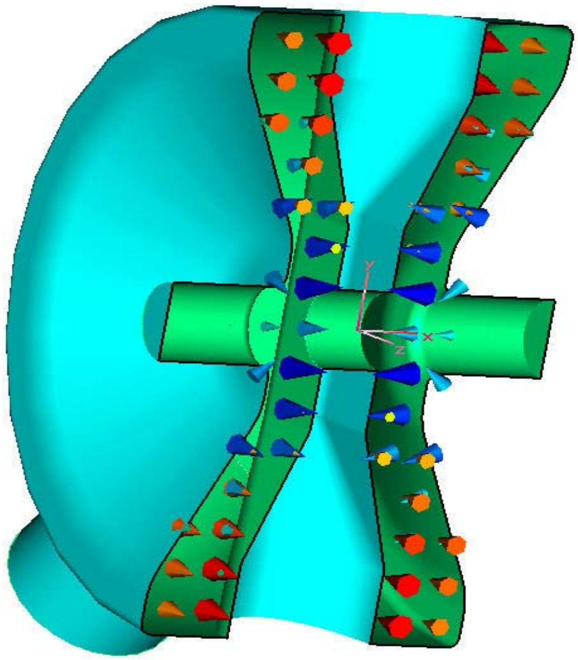
NATIONAL LABORATORY

Proceedings: Workshop on the Advanced Design of Spoke Resonators

Los Alamos, NM, USA
October 7 and 8, 2002



Editor: Frank Krawczyk, LANL

Foreword

In the last few years spoke resonators became serious candidates as accelerating structures for low velocity proton and ion beams. Starting from the early work by Jean Delayen and Ken Shepard and their colleagues various designs at different frequencies and betas have been demonstrated in low power tests. With the consideration of these resonators in recent linac designs (ATW, ESS, EURISOL, RIA, XADS) the next steps have to be taken to demonstrate their usefulness on real accelerators.

We organized this workshop to exchange and develop ideas that help demonstrating the value of these resonators in more realistic environments.

The attendance at this workshop represented all US and international groups that work in this field or that consider spoke resonators for their projects. The presentations at this workshop gave a very good overview on the progress that has been made in this field during the last few years. A wide range of different designs has been presented. The tests showed that with high standards for cleaning, spoke resonators are candidates for a reliable operation at gradients around 10 MV/m. The next generation of these resonator designs includes an extension of the technology to multigap spoke resonators with 2 or more spokes for higher real-estate gradients; and an extension to much higher betas up to 0.5 or higher. The latter is possible due to the large inherent stiffness of spoke resonators that reduce Lorentz Force Detuning and microphonics issues and thus makes them competitive or even superior to elliptical cavities for this velocity range. The presentations also demonstrated the progress made in understanding and developing the auxiliary components, like cryomodules, tuners and power coupler that are needed to operate spoke resonators on an accelerator.

These (electronic only) proceedings include the program for the 2 days of the workshop, the participant list, as well as abstracts, viewgraphs and discussion protocols for all presentations.

Frank L. Krawczyk
November 22, 2002

Participants

There was a total of 35 participants from 10 different laboratories and 3 companies. 25 of them were doing presentations or were chairing sessions. The participants came from 6 different countries: USA (18), Italy (6), France (5), Germany (4), Japan (1), Spain (1). Below you find an alphabetic listing by institution.

ACCEL:
Hanspeter Vogel

AES:
John Rathke
Tom Schultheiss

ANL:
Joel Fuerst
Mike Kelly
Ken Shepard

FZ Juelich:
Evgeny Zaplatin

INFN Legnaro:
Giovanni Bisoffi
Alberto Facco

INFN Milano:
Danilo Barni
Carlo Pagani
Paolo Pierini

Jlab:
Jean Delayen

LANL:
Mike Cappiello
Bob Garnett
Pat Kelley
Frank Krawczyk
Sergey Kurennoy
John Ledford
Debbie Montoya
George Neuschaefer
Dale Schrage
Alan Shapiro
Tsuyoshi Tajima
Tom Wangler

LLNL:
Brian Rusnak

MSU:
Terry Grimm
Felix Marti

Orsay:
Jean-Luc Biarrotte
Sebastien Bousson
Tomas Junquera
Jean Lesrel
Guillaume Olry

University of Frankfurt:
Andreas Sauer

Zanon:
Giorgio Corniani

Acknowledgments

For the local organization I want to thank Angelina Gurule-Sanchez, Lynette Trujillo, Dale Schrage and Tsuyoshi Tajima for their support. Without their help and criticism I could not have organized this meeting. John Ledford and Bruce Baille supported the videotaping of the workshop. Lynette Trujillo also helped with the proceedings.

From outside of Los Alamos I got a lot of help from Ken Shepard from ANL, Jean Delayen from Jlab and Brian Rusnak from Livermore. Without their comments the program would not be so nicely structured.

I finally want to thank all speakers and chair-people to help make this a fruitful meeting.

Workshop Program

Introduction

Frank Krawczyk: "*Introduction to the Workshop*"
(Viewgraphs)

Introduction

Frank Krawczyk

LANL

Workshop on the Advanced Design of Spoke Resonators

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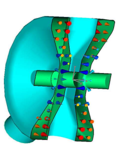
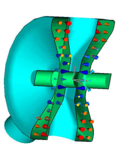


Purpose

In the last few years spoke resonators became serious candidates as accelerating structures for low velocity proton and ion beams. Starting from the early work by Jean Delayen and Ken Shepard and their colleagues various designs at different frequencies and betas have been demonstrated in low power tests. With the consideration of these resonators in recent linac designs (ATW, ESS, EURISOL, RIA, XADS) the next steps have to be taken to demonstrate their usefulness on real accelerators.

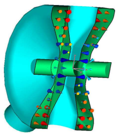
We organized this workshop to exchange and develop ideas that help demonstrating the value of these resonators in more realistic environments.



Workshop Scope

What could we get out of this workshop?

- Better (more efficient) ways to design spoke resonators
- Understanding, when “simple” is enough (vs. “optimal”)
- Lessons learned
- Things to avoid
- Observations we need to understand
- Integration of cavities and couplers
- Integration with ancillary components (tuners, stiffening, …)
- Useful future experiments/designs
- Explain to Paolo that he needs to go to Zanon this year



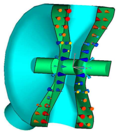
Workshop Format

The workshop is structured in

- Overview talk
- Status of projects
- Technical design details of:
  - Spoke resonators
  - Ancillary components
  - Cryo-systems
- Test results

Each presentation allows for 5 to 10 minutes of discussion. And there are several dedicated discussion sessions. The presentations should help initiate fruitful discussion.

While there will be no proceedings, we are planning to publish a CD-ROM with all the presentations. We will also publish a summary of the discussion sessions.

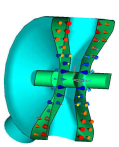


Miscellaneous

- Emergency Exits

- Acknowledgements:
  - Angelina Gurule-Sanchez, Lynnette Trujillo, Dale Schrage, Tsuyoshi Tajima
  - Ken Shepard, Jean Delayen and Brian Rusnak
  - All speakers chair-people and participants

- Dinner at “Rancho de Chimayo” at 7:00 PM (see map in the abstract booklet)



Workshop Program

				1st DAY - AM		
Time	**Talk**	**Disc.**	**Topic**		**Speaker**	**Chair**
8:30	0:05	0:00	Welcome		M. Cappiello	
8:35	0:10	0:00	Introduction		F. Krawczyk	
8:45	0:20	0:05	Overview	Medium-β SC Structures	J. Delayen	F. Krawczyk
9:10	0:10	0:05	Status of Projects	ANL:RIA	K. Shepard	F. Krawczyk
9:25	0:10	0:05		CNRS:XADS/Eurisol	T. Junquera	
9:40	0:10	0:05		FZJ:ESS	E. Zaplatin	
9:55	0:10	0:05		LANL:AAA	D. Schrage	
10:10	0:10	0:05		INFN-Milano:TRASCO	P. Pierini	
10:25	0:00	0:15	Break			
10:40	0:10	0:05	Specific Designs	ANL:RIA	K. Shepard	J. Delayen
10:55	0:10	0:05		CNRS:XADS/Eurisol	G. Olry	
11:10	0:10	0:05		FZJ:ESS	E. Zaplatin	
11:25	0:10	0:05		LANL:AAA	F. Krawczyk	
11:40	0:10	0:05		INFN-Legnaro:Ladder/Cross	G. Bisoffi	
11:55	0:00	0:20	Discussion	RF Design Procedure	All	J. Delayen / K. Shepard
12:15	0:00	1:05	Lunch Break			

Workshop Program

				1st DAY - PM		
Time	Talk	Disc.	Topic		Speaker	Chair
12:15	0:00	1:05	Lunch Break			
13:20	0:10	0:05	Mechanical Design	ANL:RIA	T. Schultheiss	J. Rathke
13:35	0:10	0:05		CNRS:XADS/Eurisol	G. Olry	
13:50	0:10	0:05		LANL:AAA	D. Schrage	
14:05	0:10	0:05	Tuner Design	ANL:RIA	B. Rusnak	M. Kelly
14:20	0:10	0:05		LANL:AAA	D. Schrage	
14:35	0:10	0:05	Fabrication	ANL:RIA	K. Shepard	J. Rathke
14:50	0:10	0:05		CNRS:XADS/Eurisol	J. Lesrel	
15:05	0:10	0:05		LANL:AAA	D. Schrage	
15:20	0:00	0:15	Break			
15:35	0:00	0:30	Discussion	Mechanical, Tuner & Fab	All	J. Delayen / K. Shepard
16:05	0:10	0:05	Test Results	LANL:AAA	T. Tajima	K. Shepard / J. Delayen
16:20	0:10	0:05		ANL:RIA	M. Kelly	
16:35	0:10	0:05	Cavity Processing	ANL:RIA	M. Kelly	
16:50	0:10	0:05		CNRS:XADS/Eurisol	S. Bousson	
17:05	0:10	0:05		LANL:AAA	T. Tajima	
17:20	0:00	0:30	Discussion	Processing&Testing	All	J. Delayen / K. Shepard
17:50			End of First Day			
19:00			Rancho de Chimayo			

Opening Talk

Jean Delayen: "*Medium Beta SC Structures*"
(Abstract | Viewgraphs | Discussion)

Medium-β SC Structures

J. Delayen, Jefferson Lab

While, originally, the development of superconducting structures was cleanly divided between low-β resonators for heavy ions and β=1 resonators for electrons, recent interest in protons accelerators (high and low current, pulsed and cw) has necessitated the development of structures that bridge the gap between the two. These activities have resulted both in new geometries and in the adaptation of well-known geometries optimized for this intermediate velocity range. Their characteristics and properties are reviewed.

MEDIUM-β SUPERCONDUCTING ACCELERATING STRUCTURES

Jean Delayen
Jefferson Lab

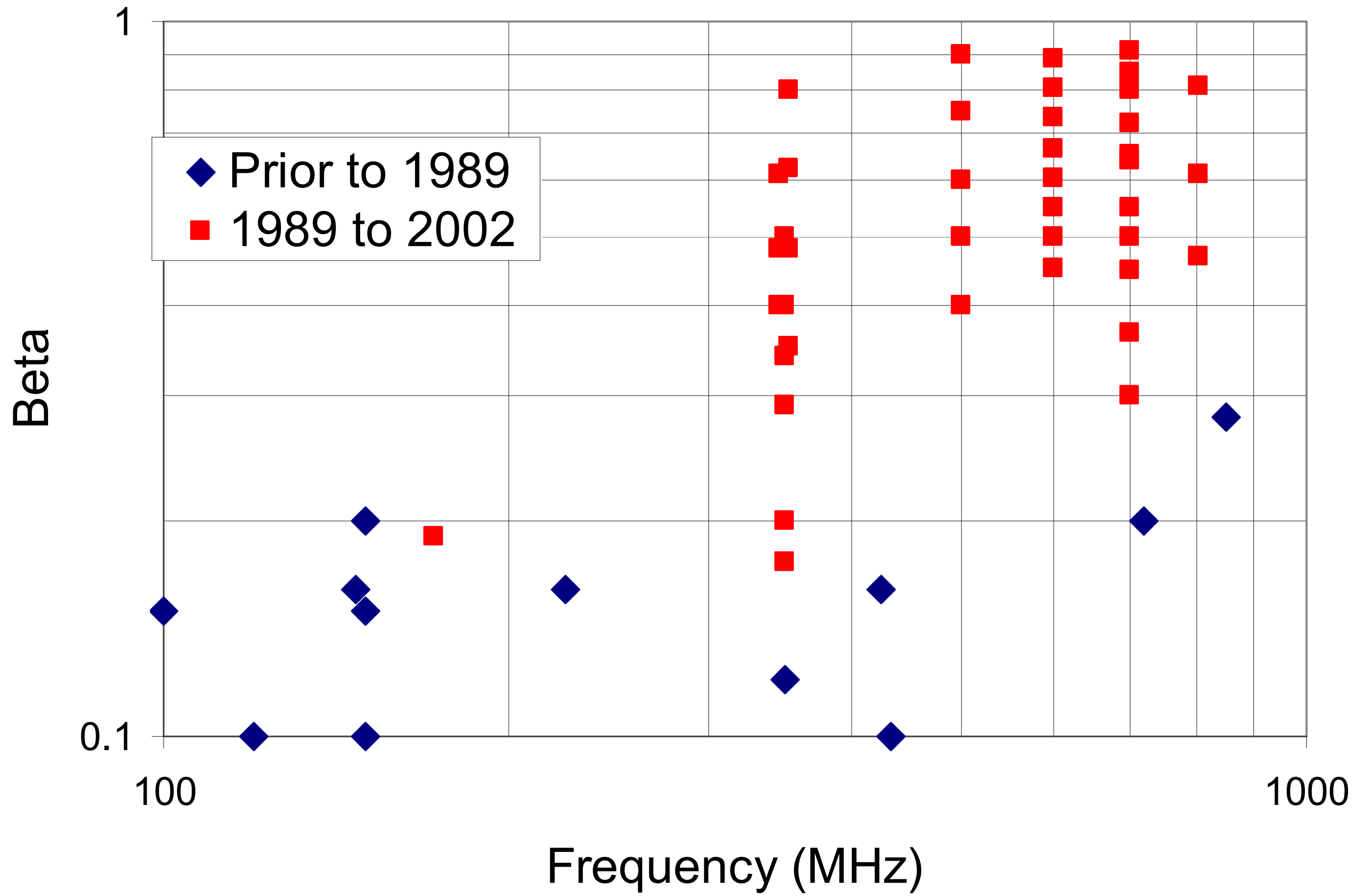
Spoke Resonator Workshop
Los Alamos

7-8 October 2002

Outline

- Historical background
- Basic geometries
- Survey of properties
- Summary

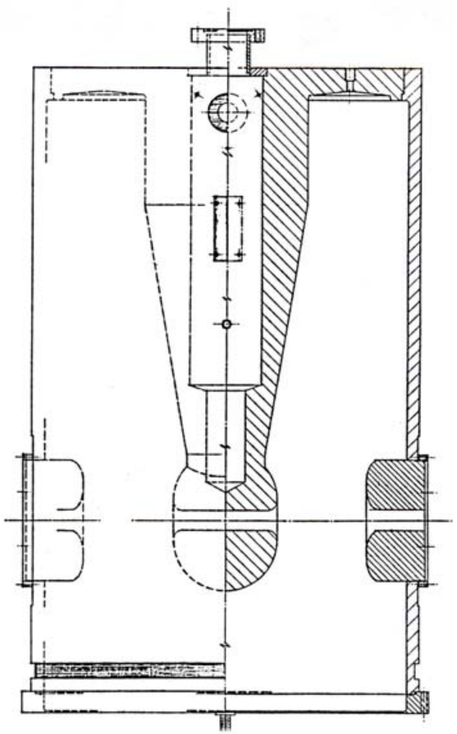
β<1 Superconducting Structures – 2002

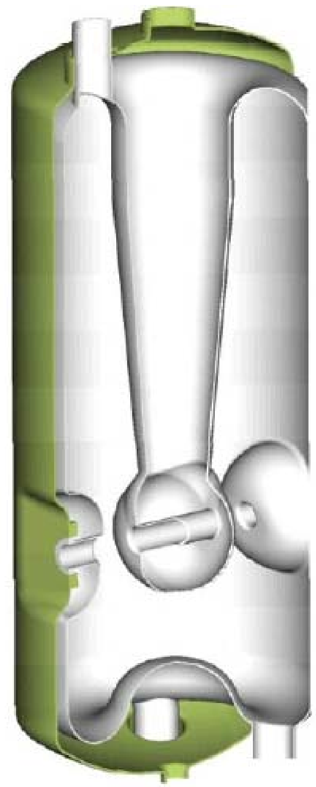


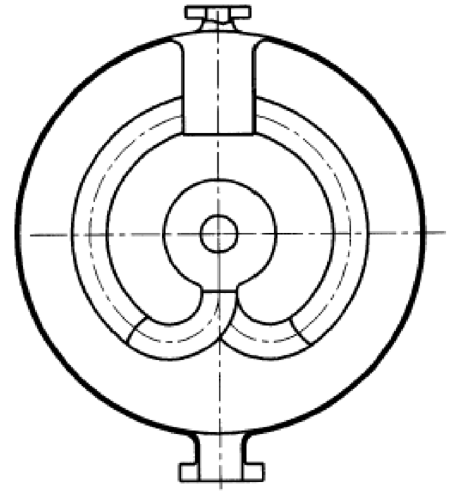
Basic Structure Geometries

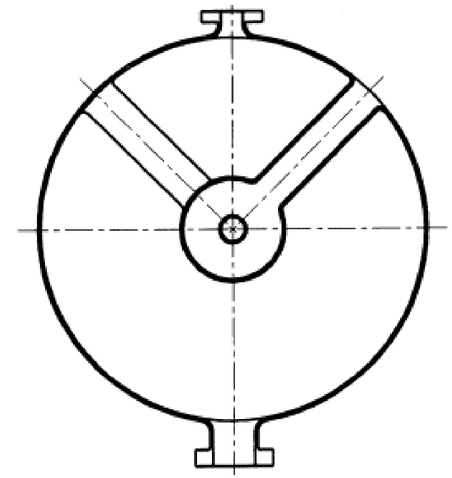
- **Resonant Transmission Lines**
  - λ/4
    - Quarter-wave
    - Split-ring
    - Twin quarter-wave
    - Lollipop
  - λ/2
    - Coaxial half-wave
    - Spoke
    - H-types
- **TM**
  - Elliptical
  - Reentrant
- **Other**
  - Alvarez
  - Slotted-iris

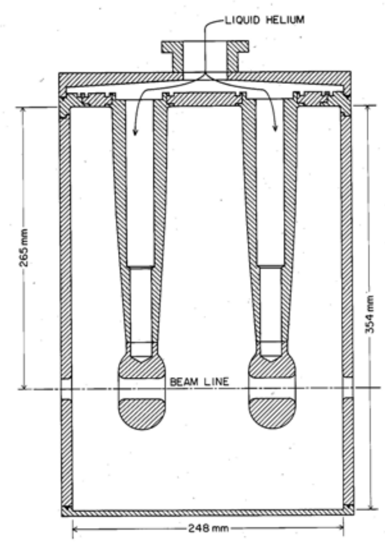
λ/4 Resonant Lines

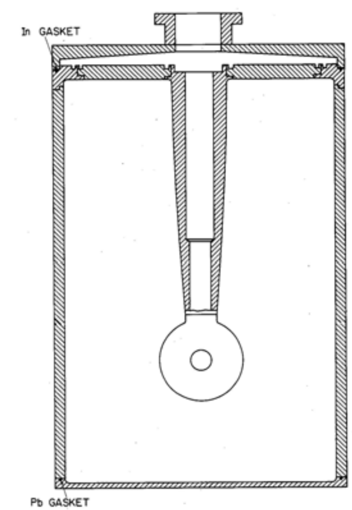




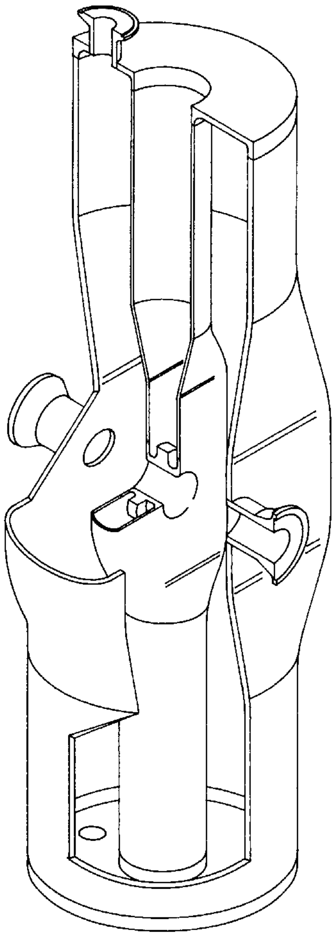


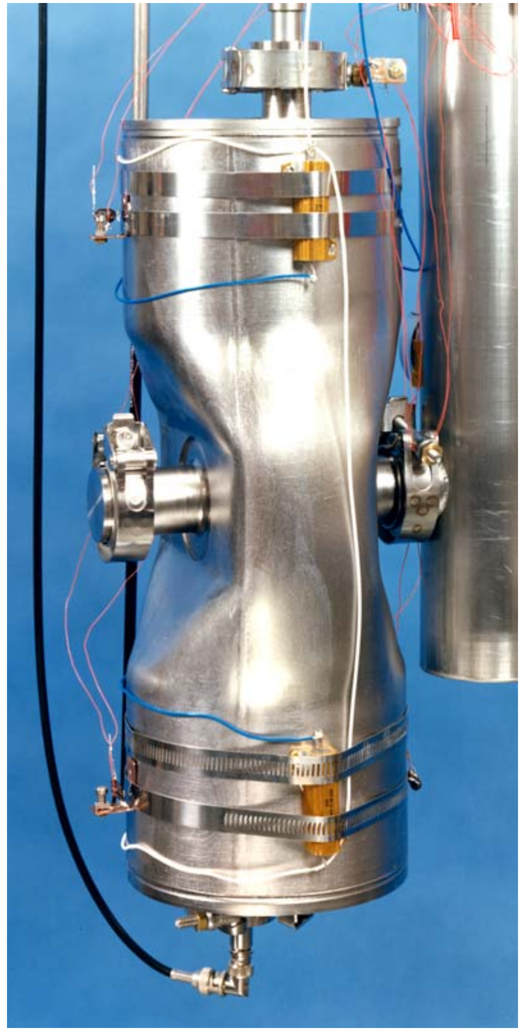


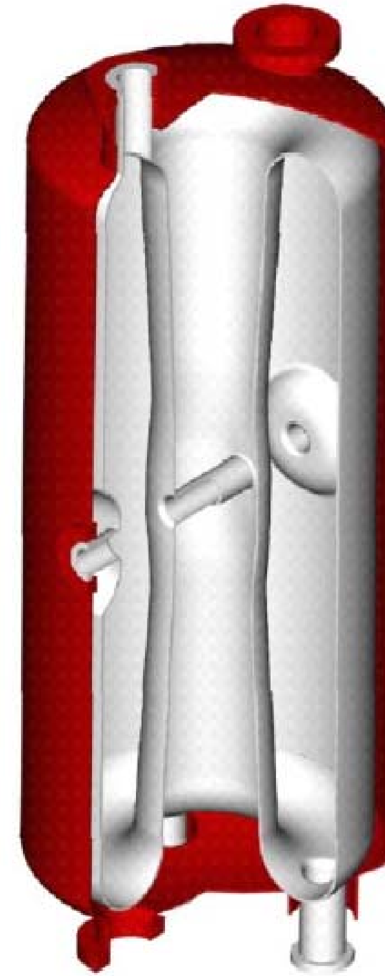




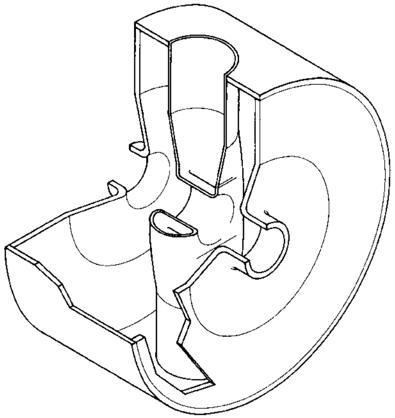
λ/2 Resonant Lines

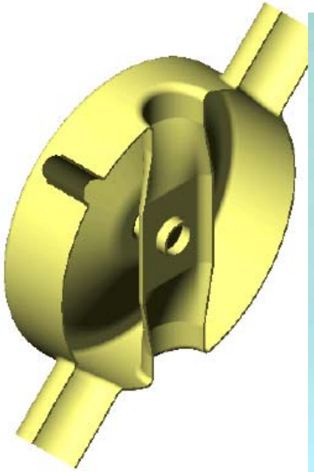


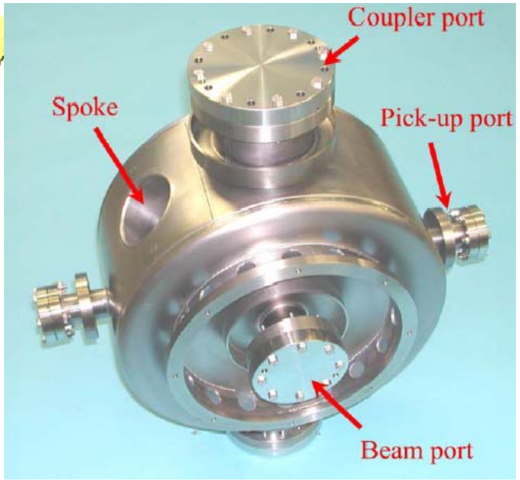




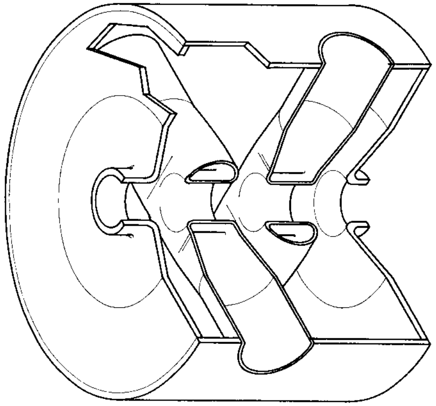
$\lambda/2$ Resonant Lines – Single-Spoke

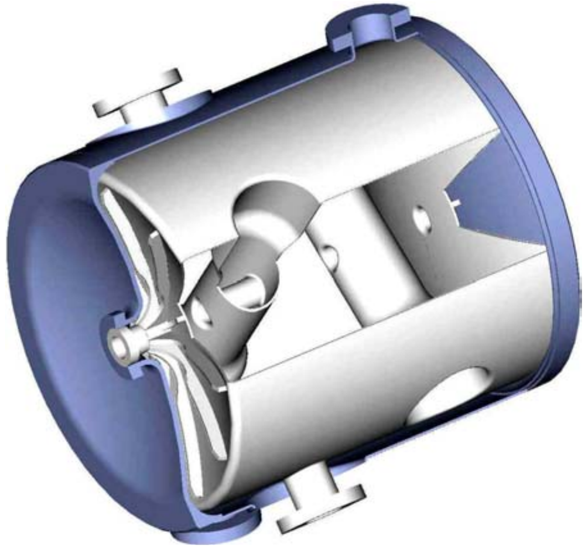


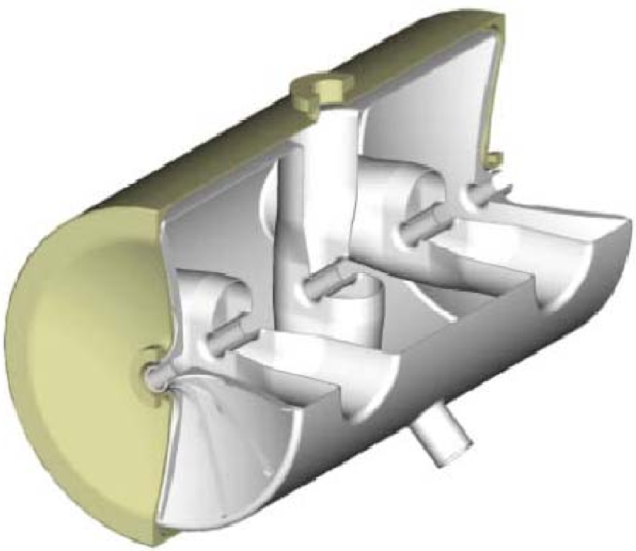




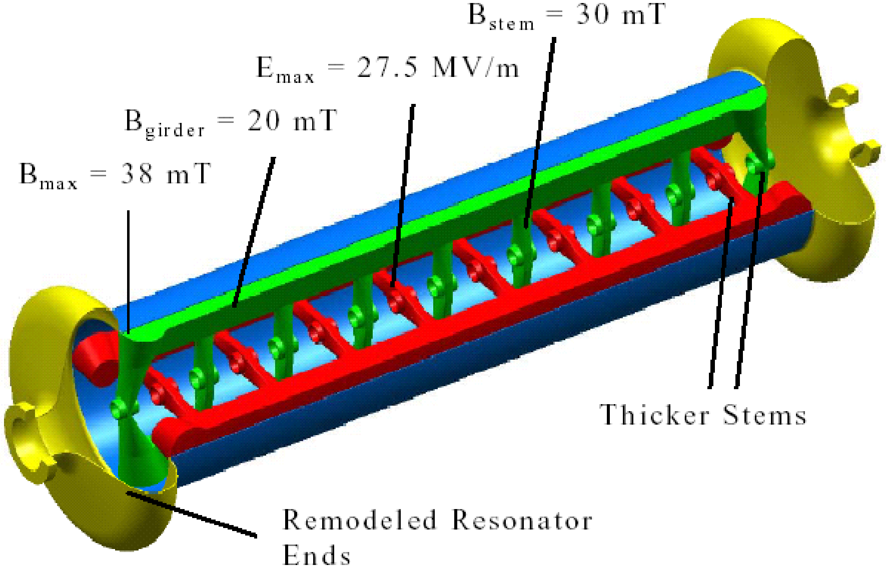
$\lambda/2$ Resonant Lines – Double and Triple-Spoke



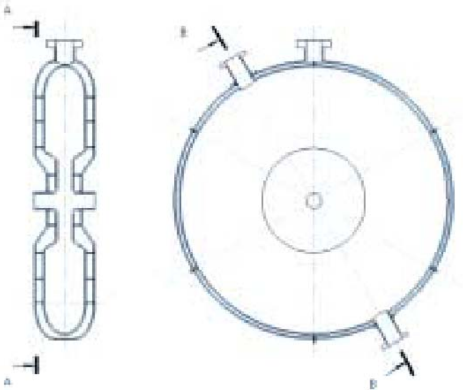




λ/2 Resonant Lines – Multi-Spoke



TM Modes



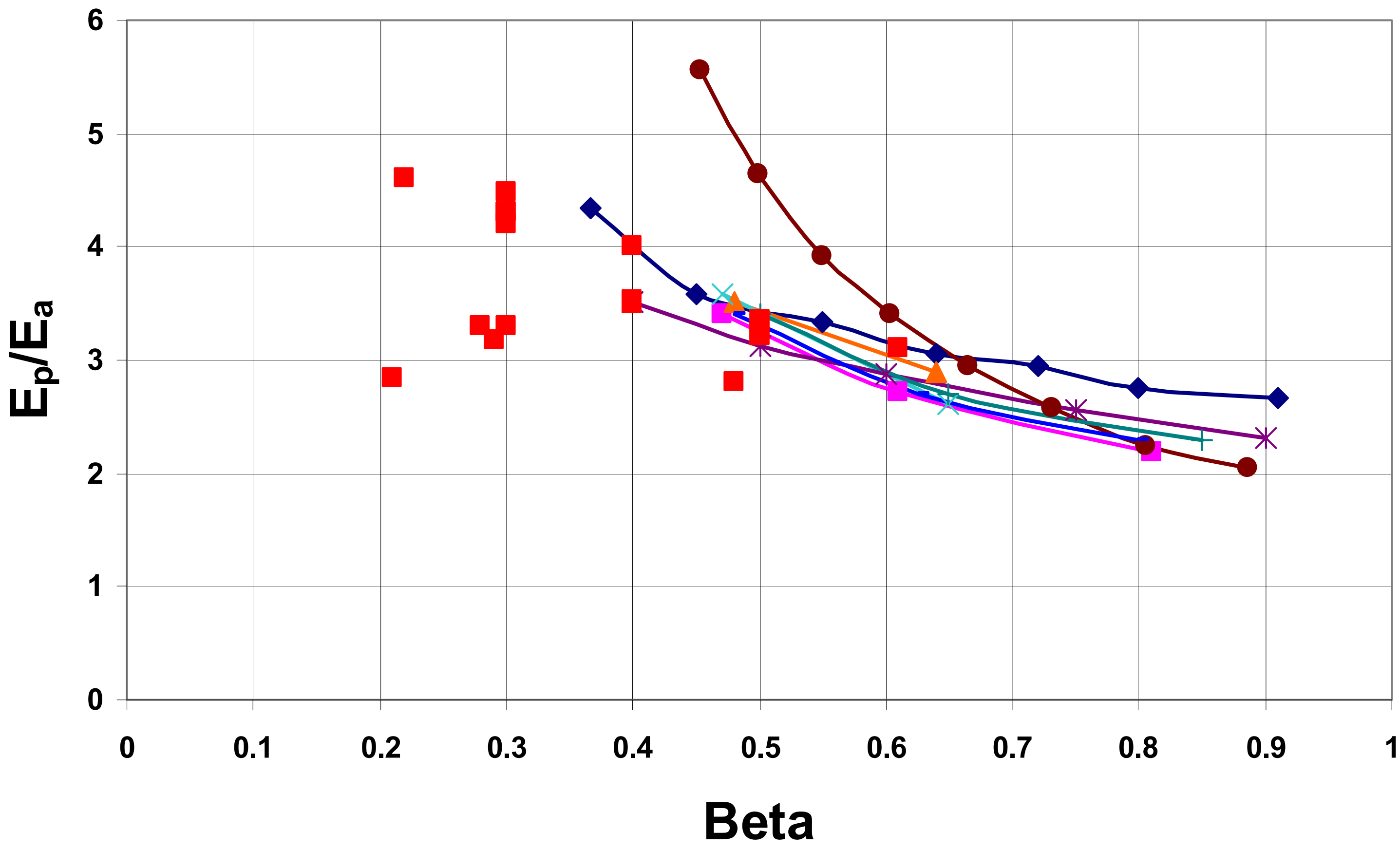
Surface Electric Field

- TM_{010} elliptical structures
  - $E_p/E_a \sim 2$ for $\beta = 1$
  - Increases slowly as β decreases

- $\lambda/2$ structures:
  - Sensitive to geometrical design
  - Electrostatic model of an "shaped geometry" gives $E_p/E_a \sim 3.3$, independent of β

Surface Electric Field

- Lines: Elliptical Squares: Spoke

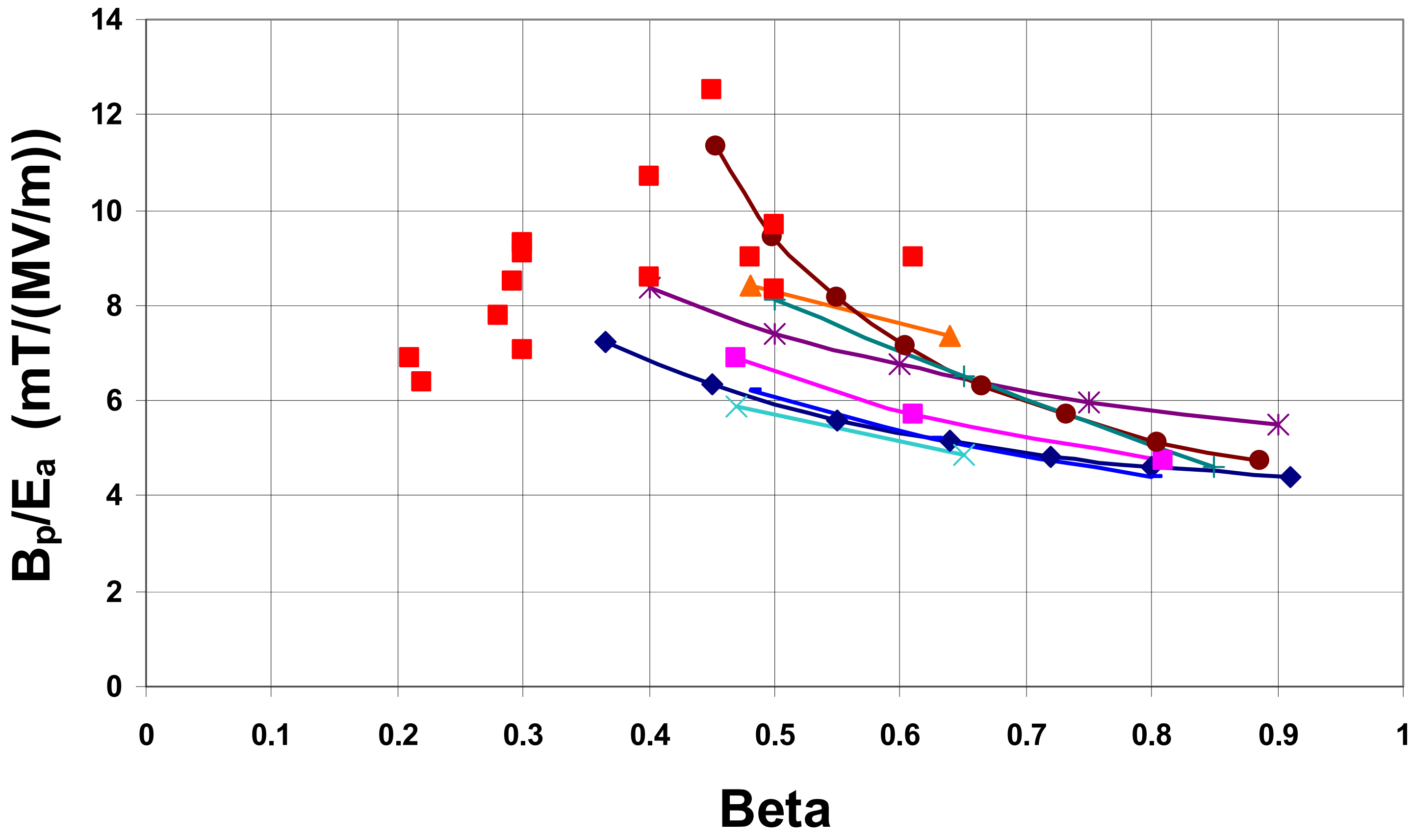


Surface Magnetic Field

- TM_{010} elliptical cavities:
  - $B/E_a \sim 4$ mT/(MV/m) for β=1
  - Increases slowly as β decreases
- $\lambda/2$ structures:
  - Sensitive to geometrical design
  - Transmission line model gives $B/E_a \sim 8$ mT/(MV/m), independent of β

Surface Magnetic Field

- Lines: Elliptical Squares: Spoke



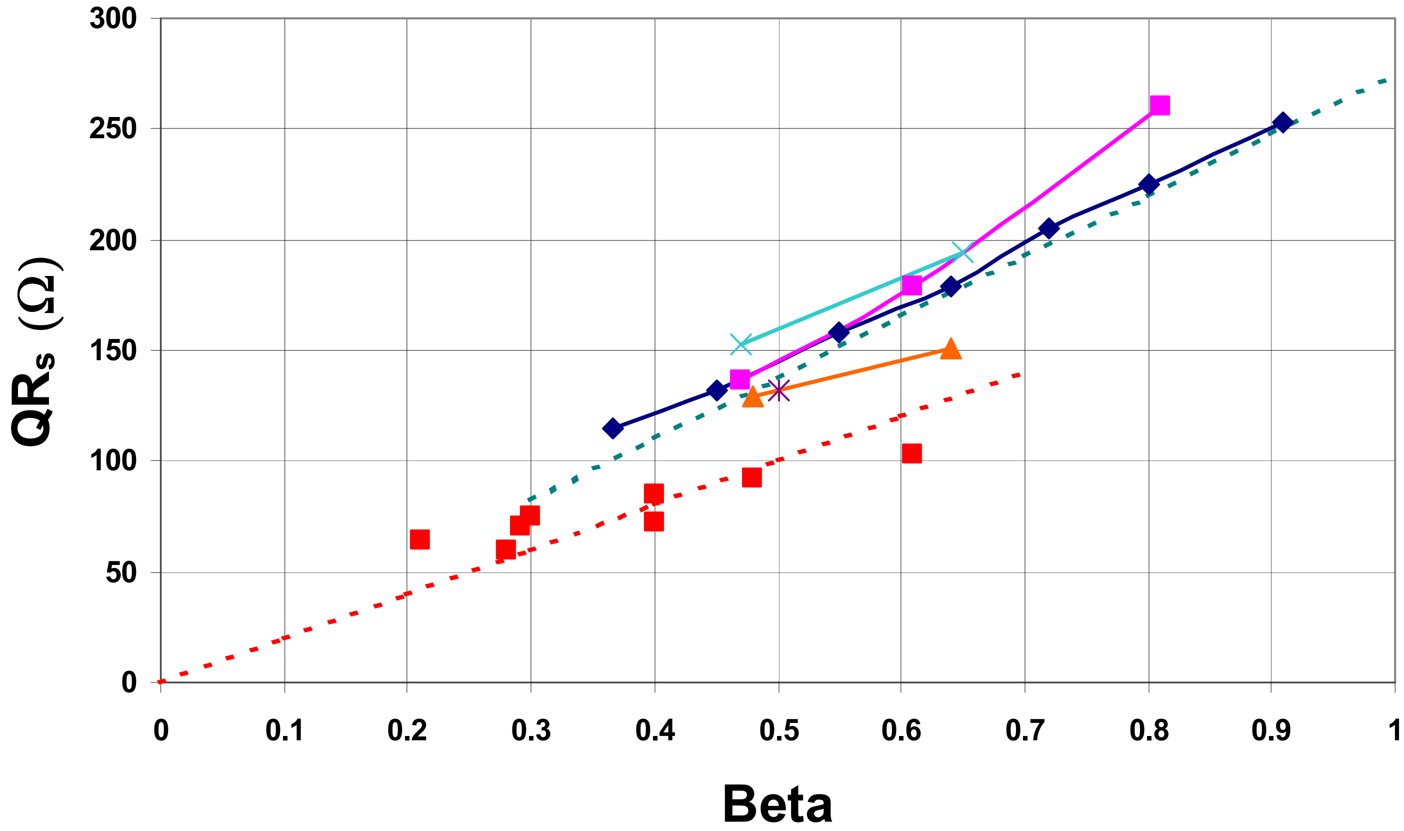
Geometrical Factor (QR_s)

- TM_{010} elliptical cavities:
  - Simple scaling: $QR_s \sim 275\ \beta\ \ (\Omega)$

- $\lambda/2$ structures:
  - Transmission line model: $QR_s \sim 200\ \beta\ \ (\Omega)$

Geometrical Factor (QR_s)

- Lines: Elliptical   Squares: Spoke



R_{sh}/Q per cell or loading element

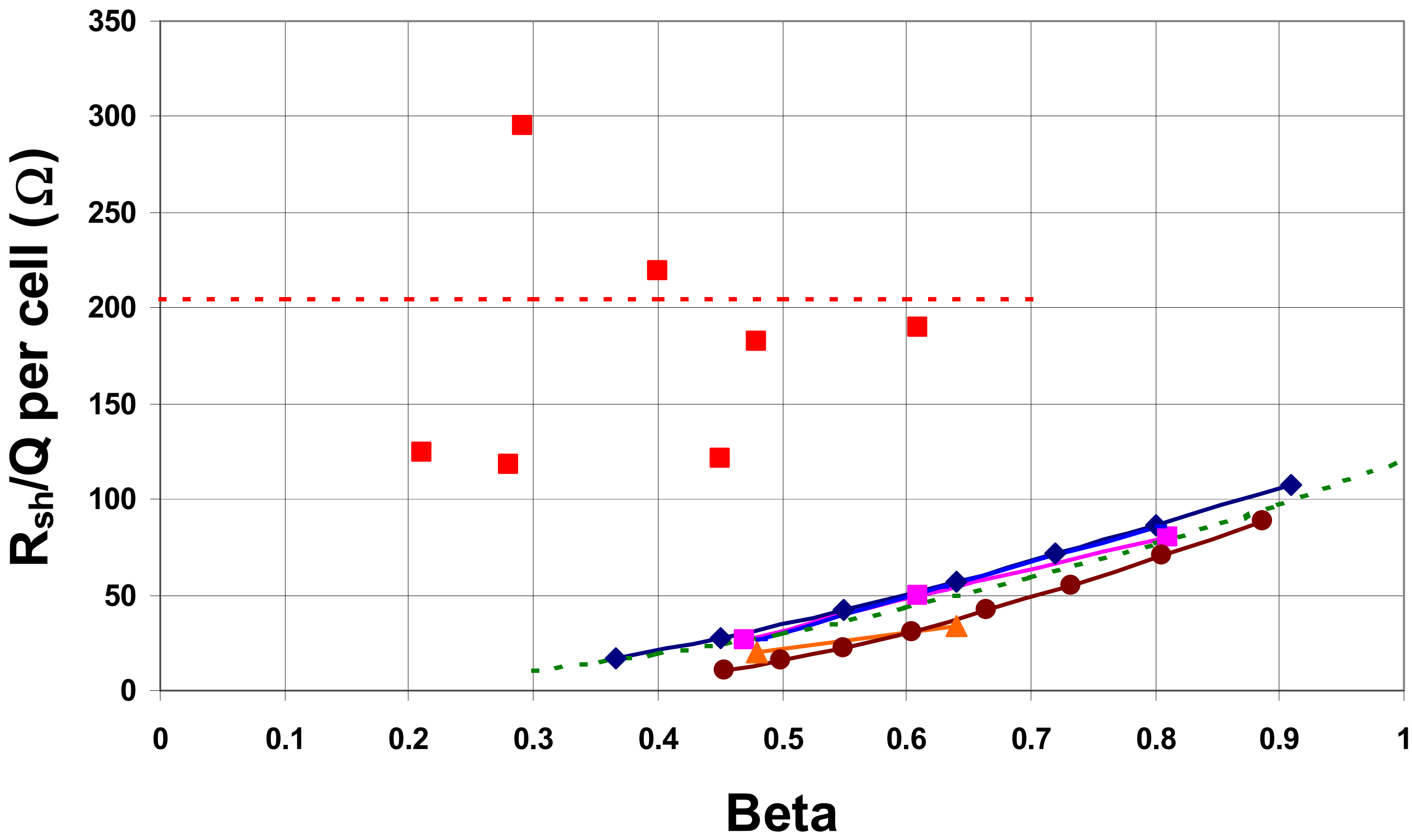
- $R_{sh} = V^2/P$

- TM_{010} elliptical cavities:
  - Simple-minded argument, ignoring effect of beam line aperture, gives : $R_{sh}/Q \propto \beta$
  - When cavity length becomes comparable to beam line aperture : $R_{sh}/Q \propto \beta^2$
  - $R_{sh}/Q \approx 120\ \beta^2 \quad (\Omega)$

- $\lambda/2$ structures:
  - Transmission line model gives: $R_{sh}/Q \approx 205\ \Omega$
  - Independent of β

R_{sh}/Q per cell or loading element

Lines: Elliptical   Squares: Spoke

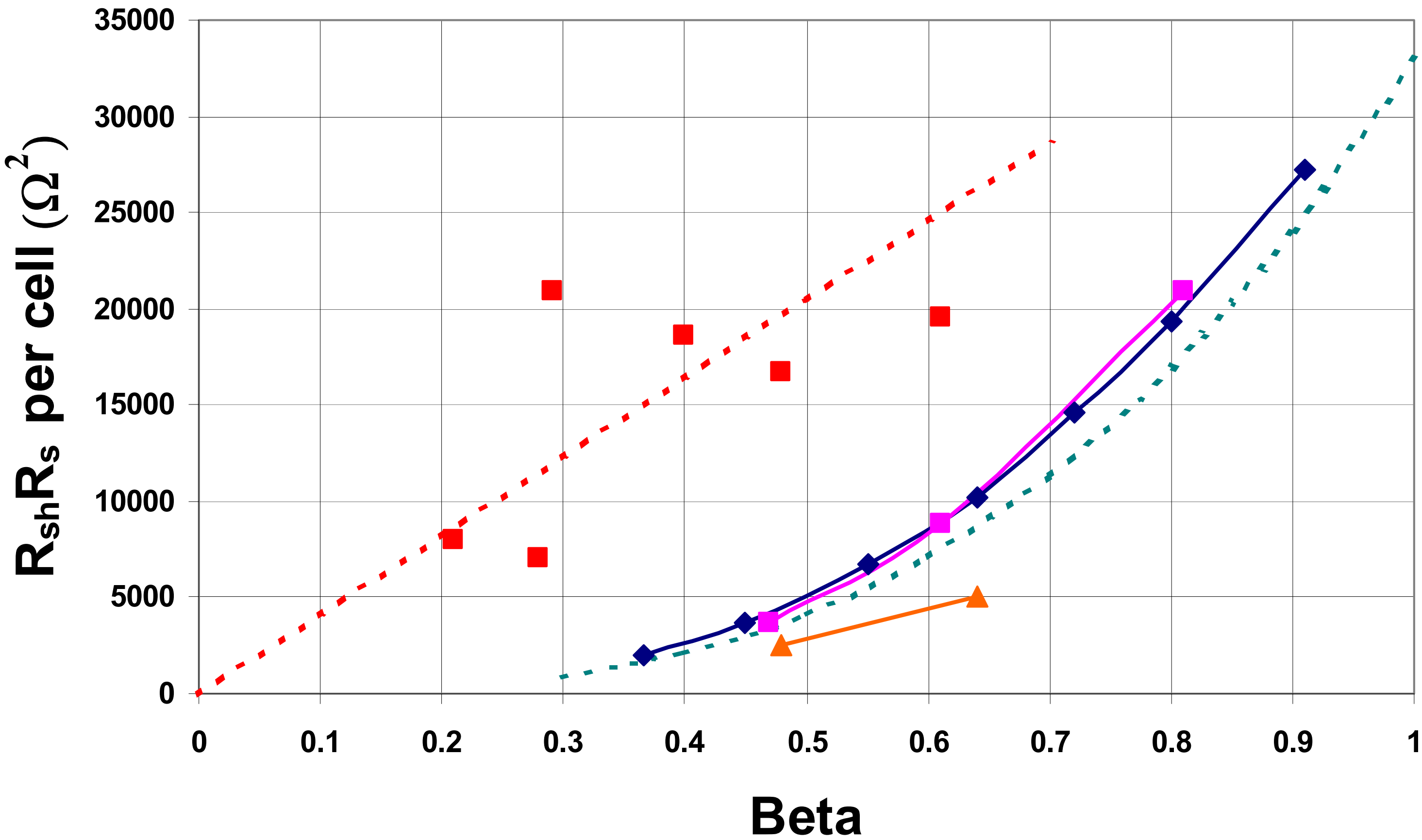


Shunt Impedance R_{sh}
(R_{sh}/Q QR_s per cell or loading element)

- TM_{010} elliptical cavities:
  - $R_{sh}\,R_s \sim 33000\,\beta^3 \quad (\Omega^2)$
- $\lambda/2$ structures:
  - $R_{sh}\,R_s \sim 40000\,\beta \quad (\Omega^2)$

Shunt Impedance R_{sh}
(R_{sh}/Q QR_s per cell or loading element)

- Lines: Elliptical Squares: Spoke



Energy Content per Cell or Loading Element

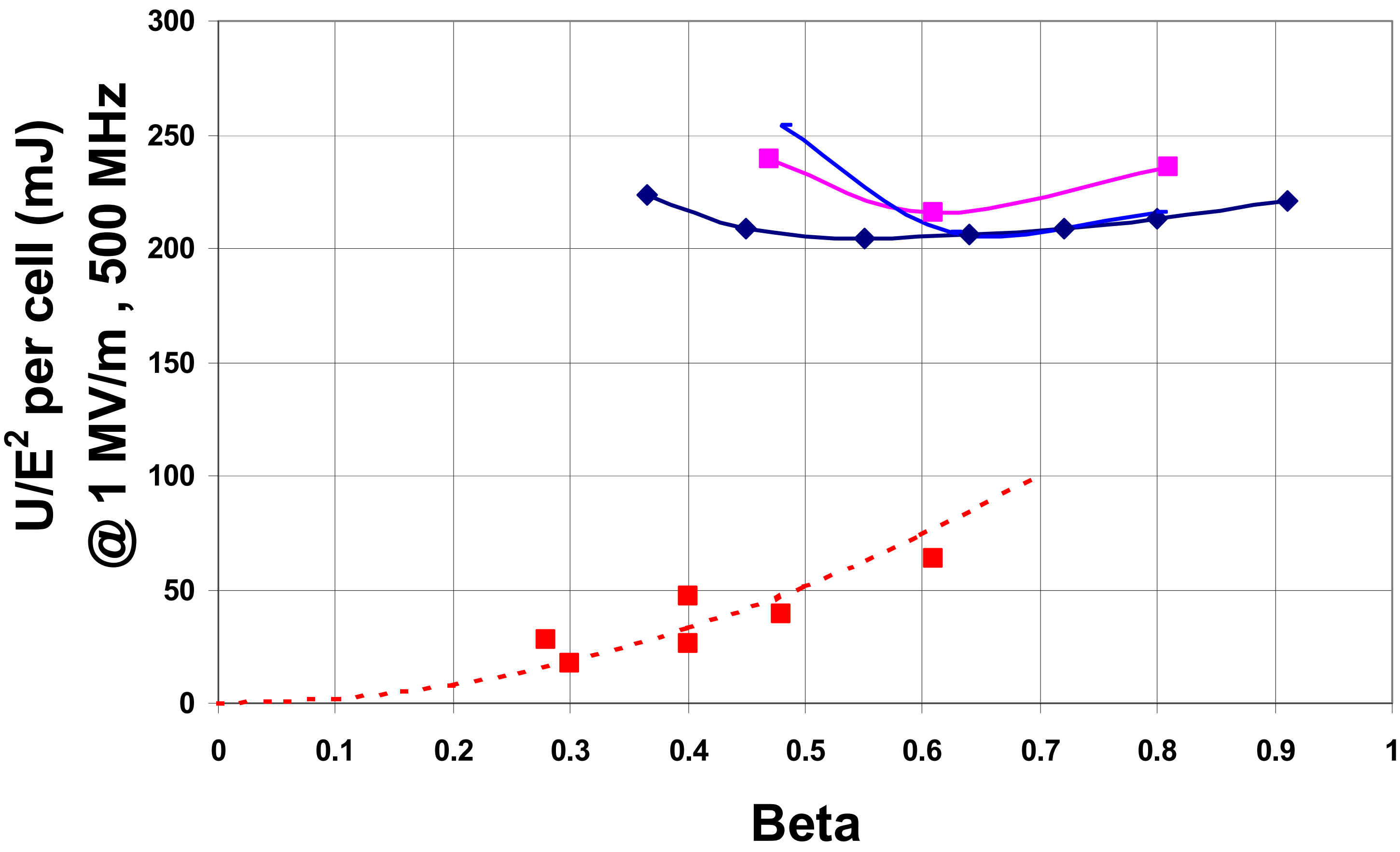
Proportional to $E^2\lambda^3$

At 1 MV/m, normalized to 500 MHz:

- TM_{010} elliptical cavities:
  - Simple-minded model gives $U/E^2 \propto \beta$
  - In practice: $U/E^2 \sim 200\text{-}250$ mJ
  - Independent of β (seems to increase when $\beta < 0.5 - 0.6$)

- $\lambda/2$ structures:
  - Sensitive to geometrical design
  - Transmission line model gives $U/E^2 \sim 200\ \beta^2$ (mJ)

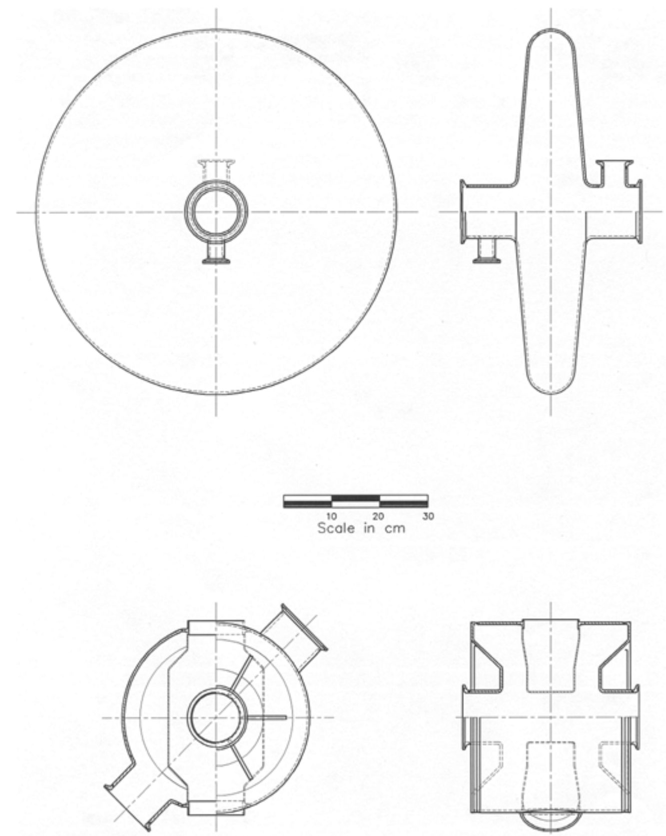
Energy Content per Cell or Loading Element



Size & Cell-to-Cell Coupling

- TM_{010} Structures
  $\varnothing \sim 0.88 - 0.92\ \lambda$
  Coupling ~ 2%

- $\lambda/2$ Structures
  $\varnothing \sim 0.46 - 0.51\ \lambda$
  Coupling ~ 20 - 30%



Example : 350 MHz, β= 0.45

Multipacting

- TM$_{010}$ elliptical structures
  - Can reasonably be modeled and predicted/avoided
  - Modeling tools exist
- $\lambda/2$ Structures
  - Much more difficult to model
  - Reliable modeling tools do not exist
  - Multipacting "always" occurs
  - "Never" a show stopper

TM Structures – Positive Features

- Geometrically simple
- Familiar
- Large knowledge base
- Good modeling tools
- Low surface fields at high β
- Small number of degrees of freedom

$\lambda/2$ Structures – Positive Features

- Compact, small size
- High shunt impedance
- Robust, stable field profile (high cell-to-cell coupling)
- Mechanically stable, rigid (low Lorentz coefficient, microphonics)
- Small energy content
- Low surface fields at low β
- Large number of degrees of freedom

What Next?

- How high in β can spoke cavities go?
- What are their high-order modes properties?
  - Spectrum
  - Impedances
  - Beam stability issues
- Is there a place for spoke cavities in high-β high-current applications?
  - FELs, ERLs
  - Higher order modes extraction

Discussion on "Medium β SC-Structures" by Jean Delayen

In the discussion Jean's plan to propose common definitions for the most relevant cavity parameters was discussed and encouraged. The proposal does not aim at establishing the same definition to be used by all projects or groups. It is aimed at establishing common (additional) parameter calculations that allow to directly compare designs by different groups.
The main point that needs a common basis for comparison is the definition of active length in a cavity. Jean will put everything on the basis of $n*\beta\lambda/2$, where n is the number of cells. This was only disputed by one comment that suggested the use of the physical length of the cavity to have a closer tie to the real estate gradient of a structure. The general agreement of the rest of the audience was that this is not practical, as the real estate gradient is mostly driven by other external components that derive from the accelerator layout (e.g. focusing elements).
Another point that needs clarification is the β of a structure. Some people tie this to the active length of a structure, which is a purely geometric quantity. The proposal from the discussion is to use the β, where the transit time factor is maximal. While this number requires the knowledge of the RF-fields to be known, it suites the purpose of the structure to structure comparison.

Status of Projects

Ken Shepard: "*RIA Project: Driver Linac Overview*"
(Abstract | Viewgraphs | Discussion)

Tomas Junquera: "*Status on Spoke Resonators R&D for two European Projects: XADS and Eurisol*"
(Abstract | Viewgraphs | Discussion)

Evgeny Zaplatin: "*SC RF Cavity Activities at FZ Juelich*"
(Abstract | Viewgraphs | Discussion)

Dale Schrage: "*The LANL Advanced Accelerator Applications (AAA) Program*"
(Abstract | Viewgraphs | Discussion)

Paolo Pierini: "*Status of the High Current Proton Accelerator for the TRASCO Program*"
(Abstract | Viewgraphs | Discussion)

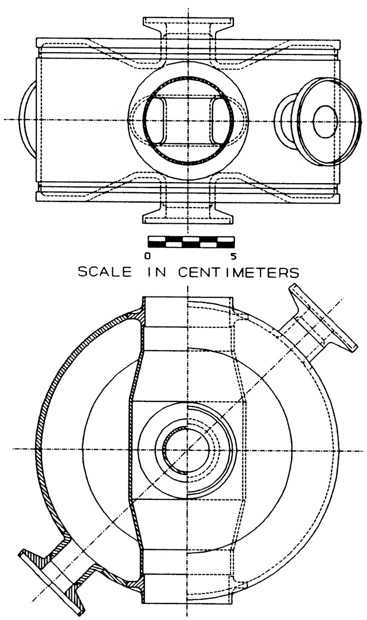
RIA Project:Driver Linac Overview

K. Shepard, Argonne National Laboratory

Current plans for the U. S. Rare Isotope Accelerator facility (RIA) call for a 1.4 GV superconducting linac which requires a mix of superconducting cavities covering the velocity range from 0.01 to 0.8 c. A design option using 345 MHz triple-spoke-loaded cavities for the high velocity section of the driver is discussed and compared with the baseline design which is based on 805 MHz elliptical-cell cavities.

Spoke Cavities at ANL - Past

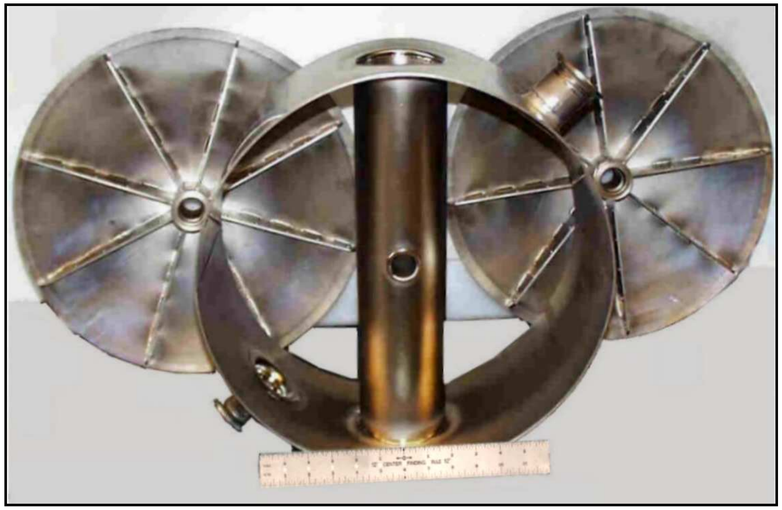
1992



855 MHz, β = 0.3
Single-spoke,
operated at 7+ MV/m
(Jean Delayen, et al.)

1998

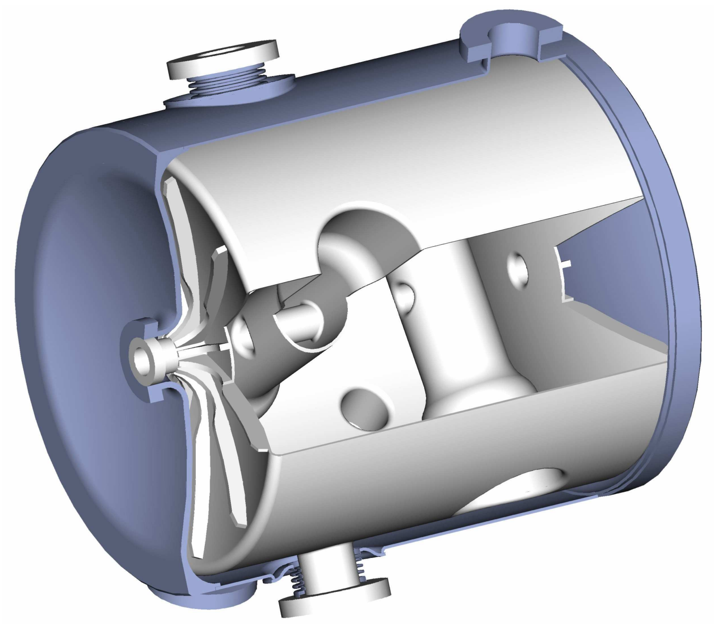
340 and 350 MHz,
β = 0.3 and β = 0.4
Single-spoke cavities
(operated at 10+ MV/m)



ANL Spoke Cavities Present & Future

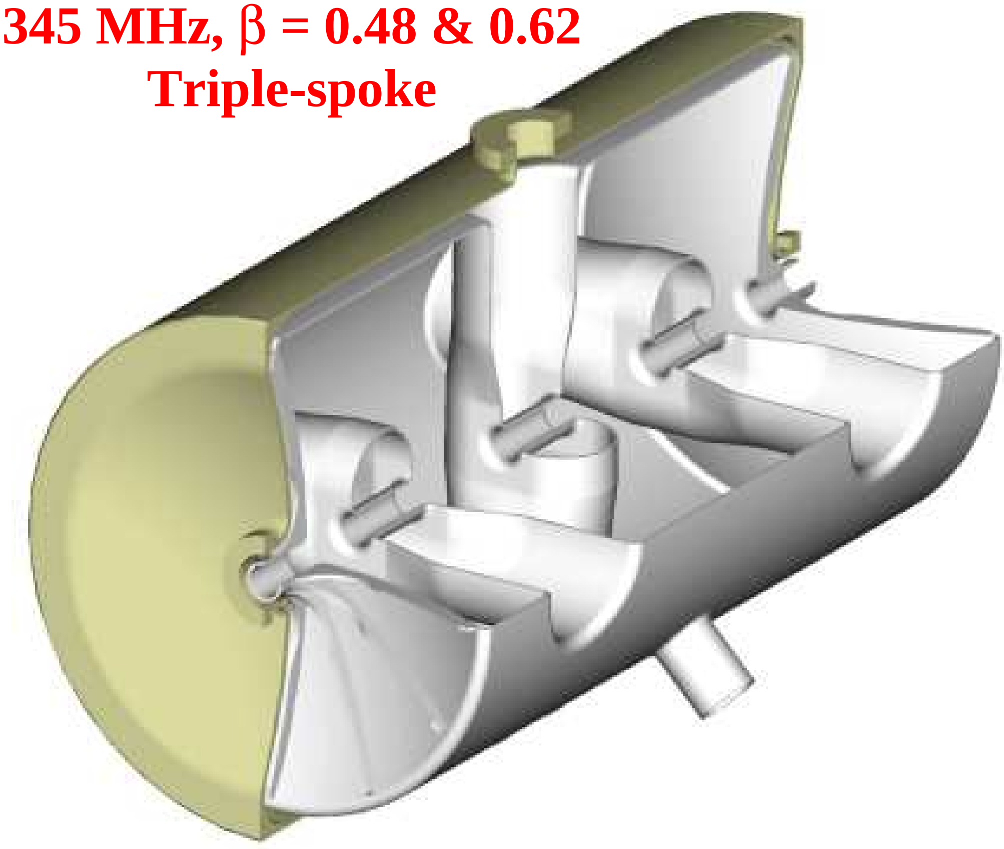
2002

Being prototyped:
345 MHz, β = 0.4
Double-spoke



2003

Proposed:
345 MHz, β = 0.48 & 0.62
Triple-spoke

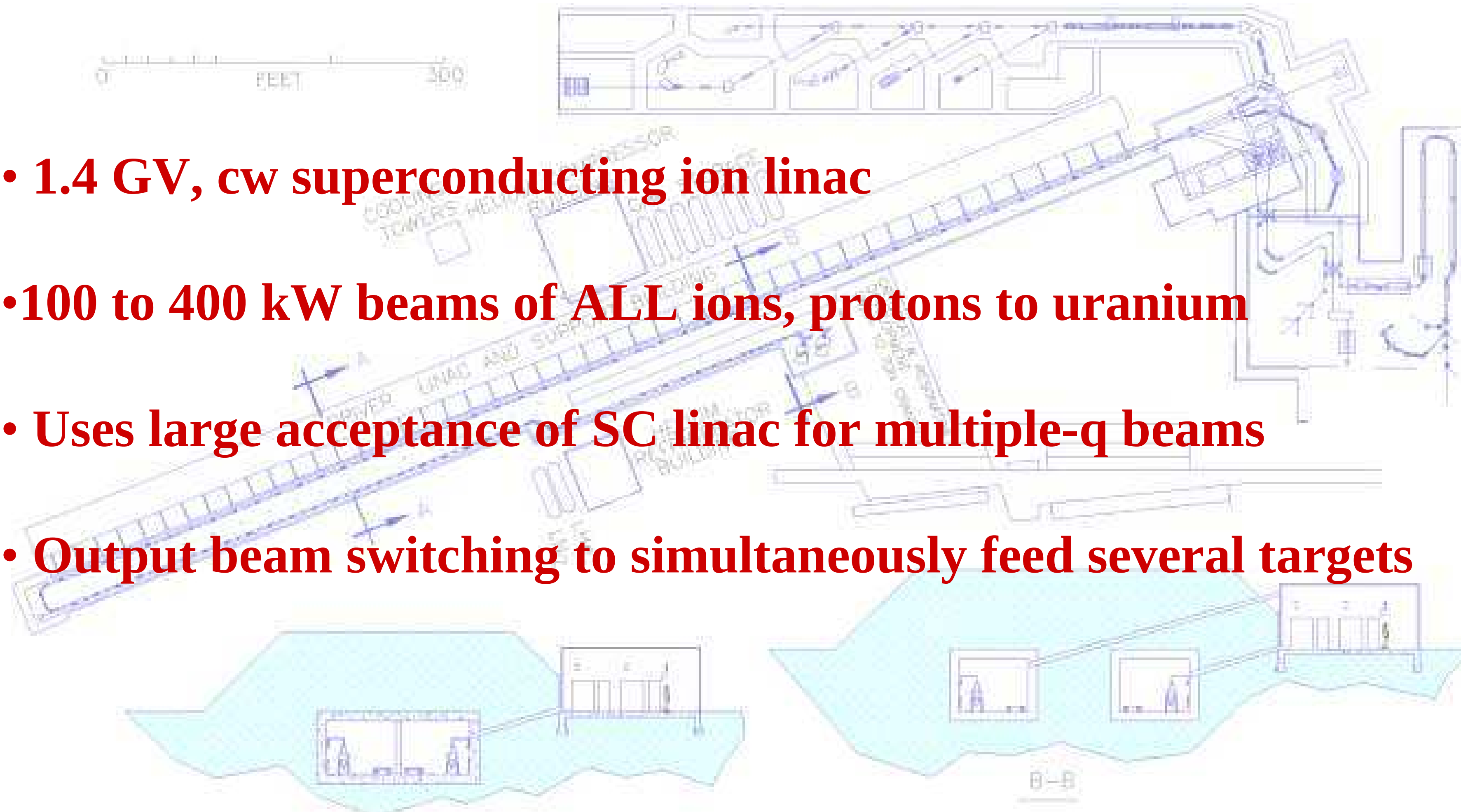


Contributers

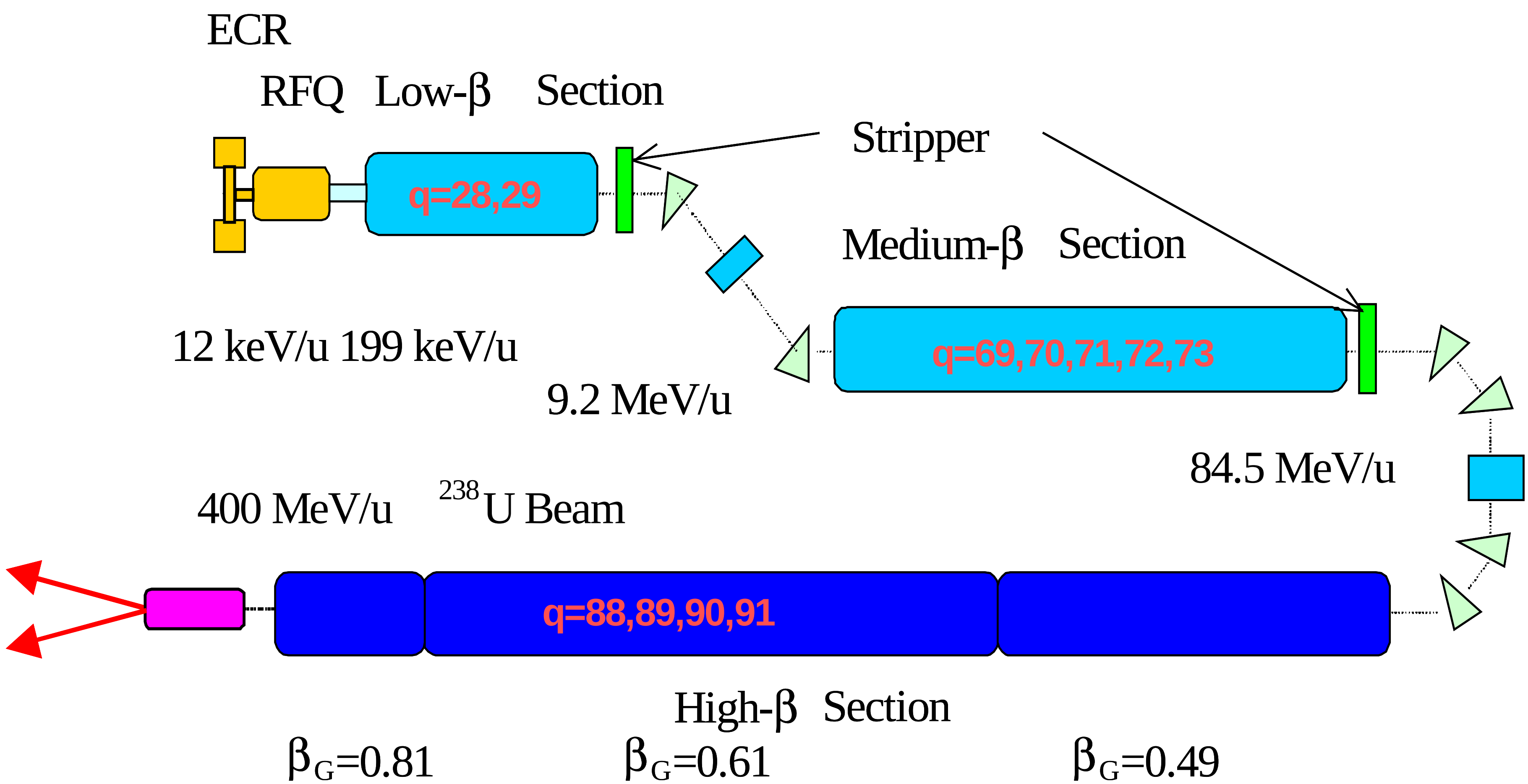
- ANL (Kelly, Fuerst, Kedzie)
- JLAB (Delayen, Brawley)
- LLNL (Rusnak)
- LANL (Schrage, Tajima, Krawcyk)
- AES (Peterson, Schultheiss, Rathke)
- Sciaky, Inc.(Hajno)

The RIA Driver Linac

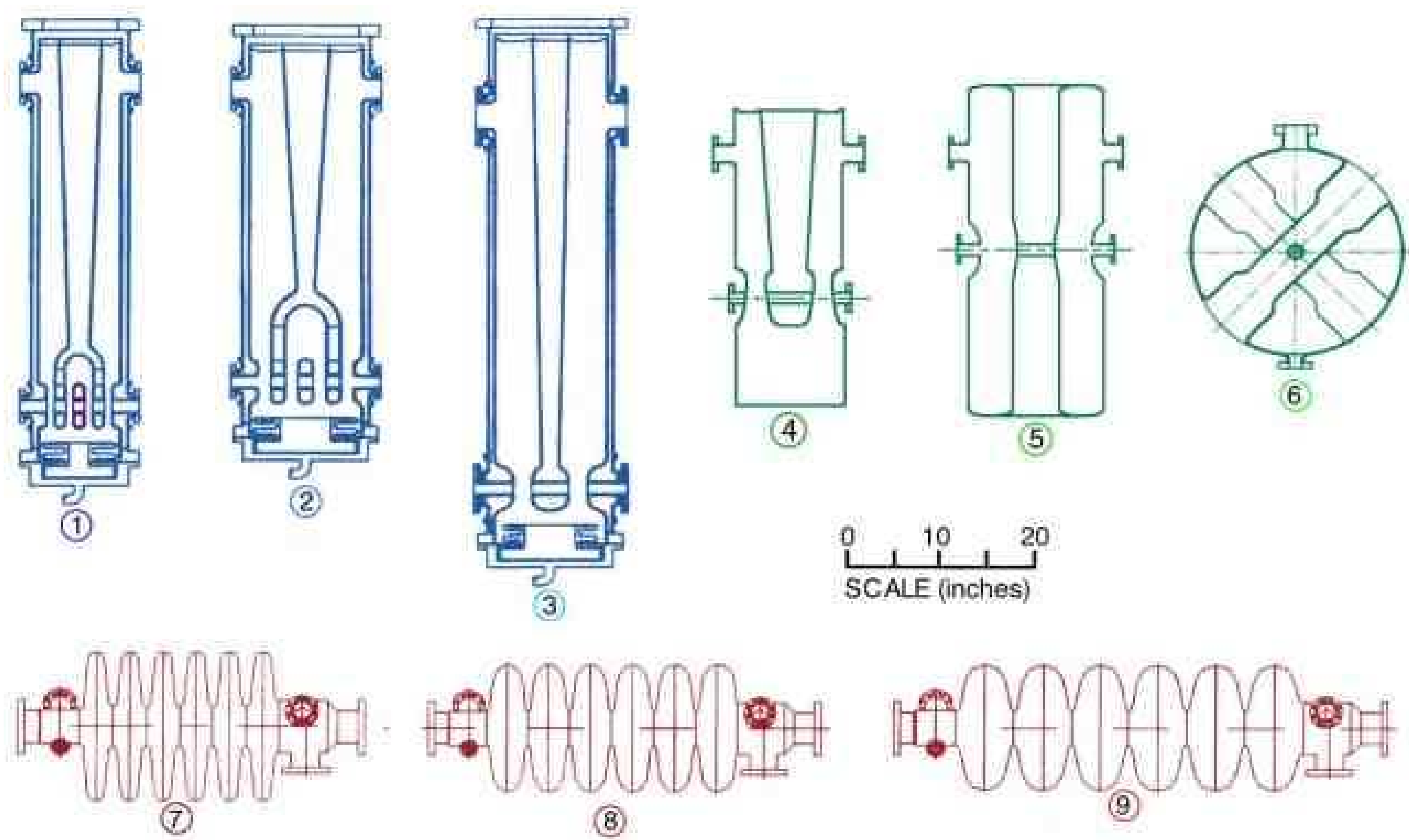
- 1.4 GV, cw superconducting ion linac
- 100 to 400 kW beams of ALL ions, protons to uranium
- Uses large acceptance of SC linac for multiple-q beams
- Output beam switching to simultaneously feed several targets



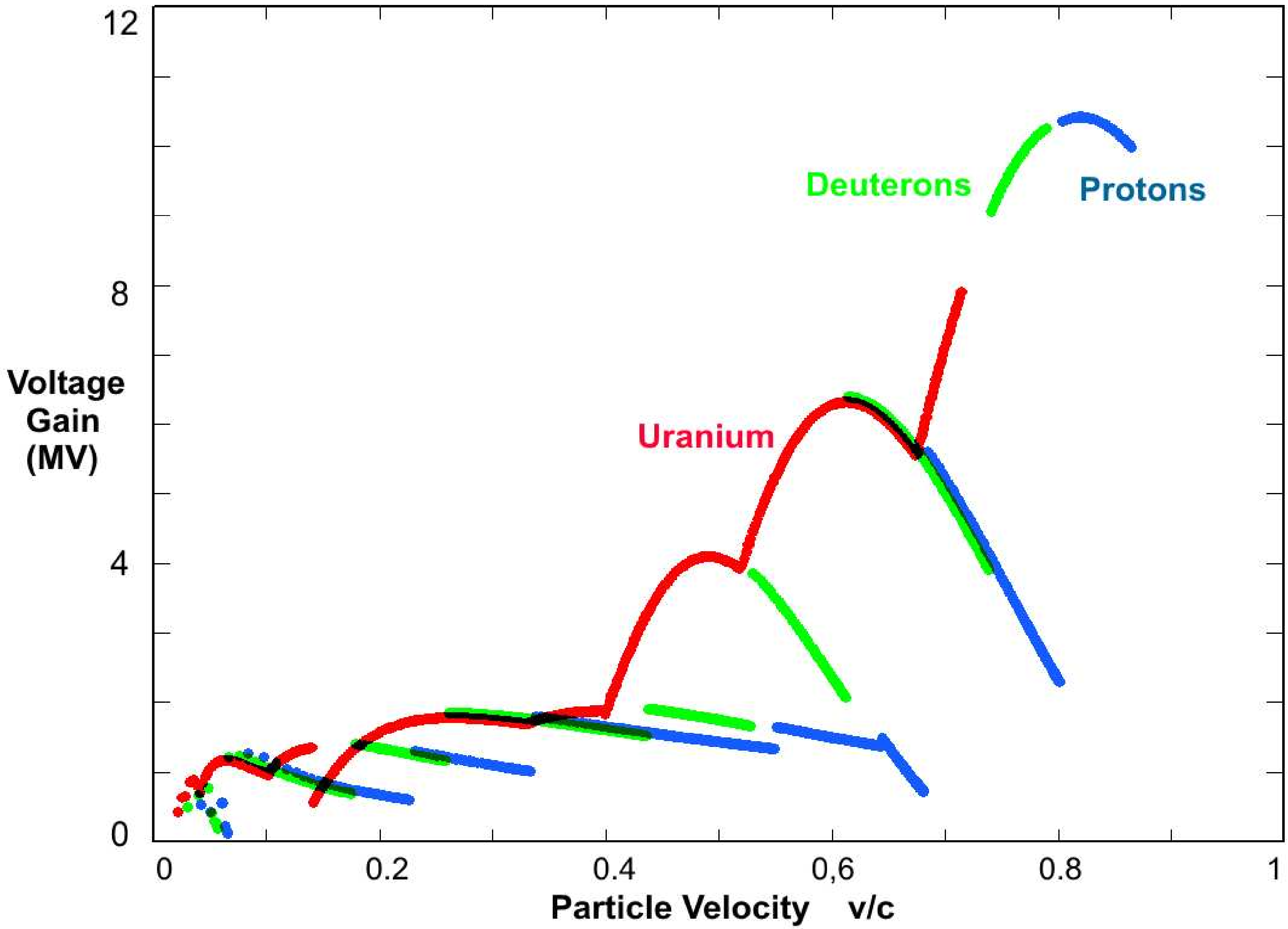
Principal Elements of the RIA Driver Linac (configured for a beam of uranium)



SC Cavity types for the RIA Driver Linac (baseline design)



“Cavity-Walk” (voltage gain per cavity) for the Baseline RIA Driver Design



Some results of the Harrison committee cost review (January 2001)

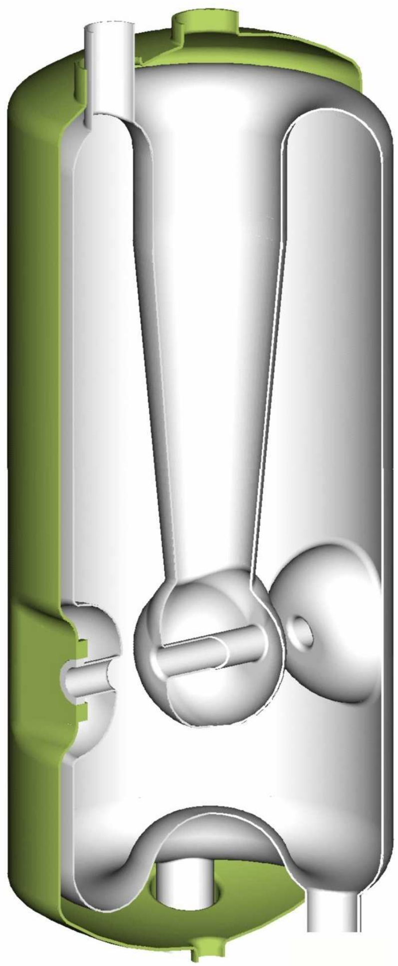
- **Much of the linac cost scales linearly with the number of cavities (cavities, couplers, rf systems, cryomodules, cryogenics, control, alignment, installation, etc.)**

- **Drift-tube linac cost = 97 M$ (with contingency)**
  - **393 k$ total cost per cavity**
  - **Cost of bare cavity averaged 24% of total**

- **Elliptical-cell Linac cost = 143 M$**
  - **762 k$ total cost per cavity**

Intermediate-velocity cavities for RIA

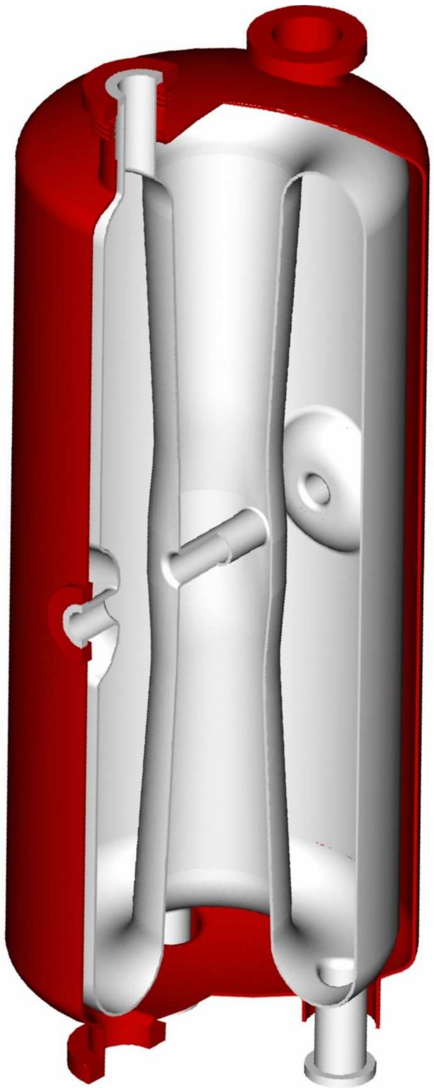
115 MHz QWR



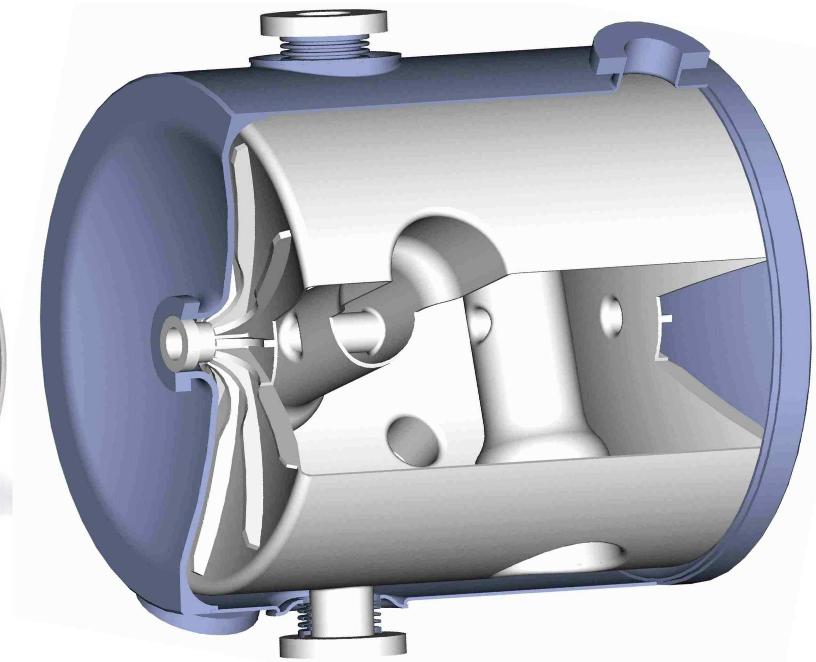
QR_S =	42
β_{Geom} =	0.15
Eff. Length =	25 cm
At 1 MV/m	
RF Energy =	170 mJ
E_{peak} =	3.17 MV/m
B_{peak} =	57 G

QR_S =	58
β_{Geom} =	0.26
Eff. Length =	30 cm
At 1 MV/m	
RF Energy =	345 mJ
E_{peak} =	2.9 MV/m
B_{peak} =	78 G

172.5 MHz HWR



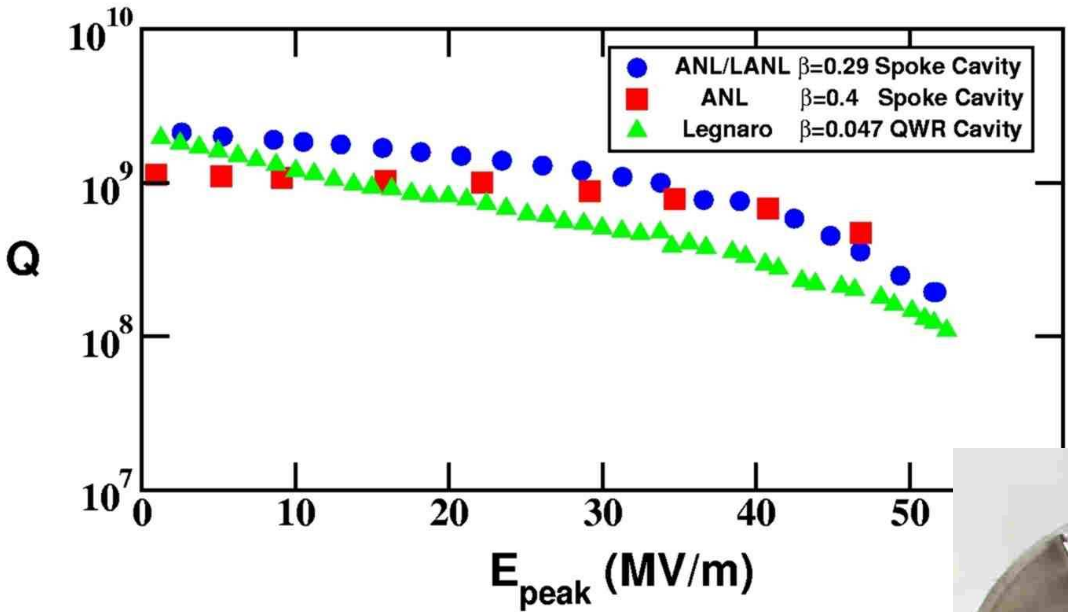
Double-spoke for the RIA Driver Linac



QR_S =	71
β_{Geom} =	0.393
Eff. Length =	38.1 cm
At 1 MV/m	
RF Energy =	151 mJ
E_{peak} =	3.47 MV/m
B_{peak} =	69 G

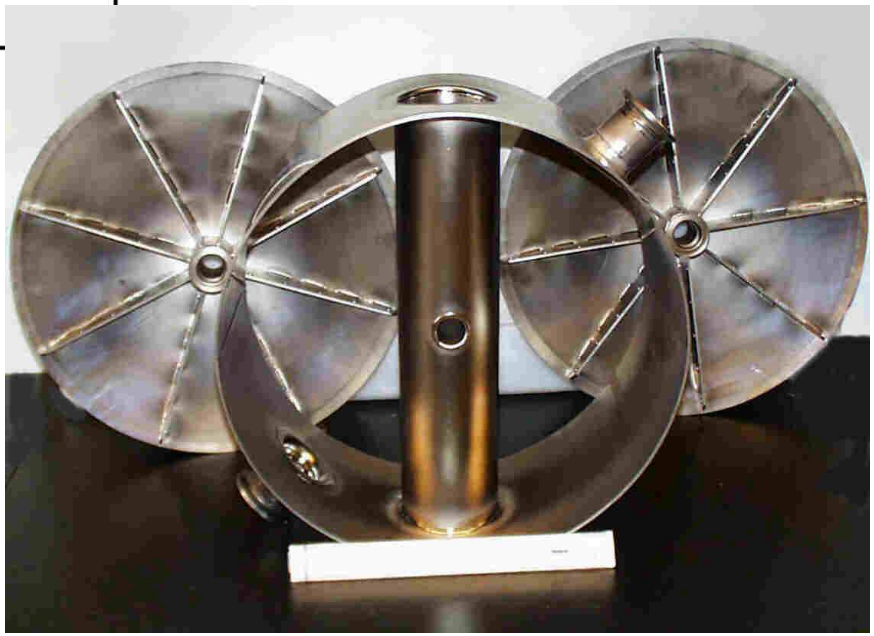
345 MHz β = 0.4 Niobium cavity being prototyped for the RIA linac

Higher gradients in drift-tube cavities

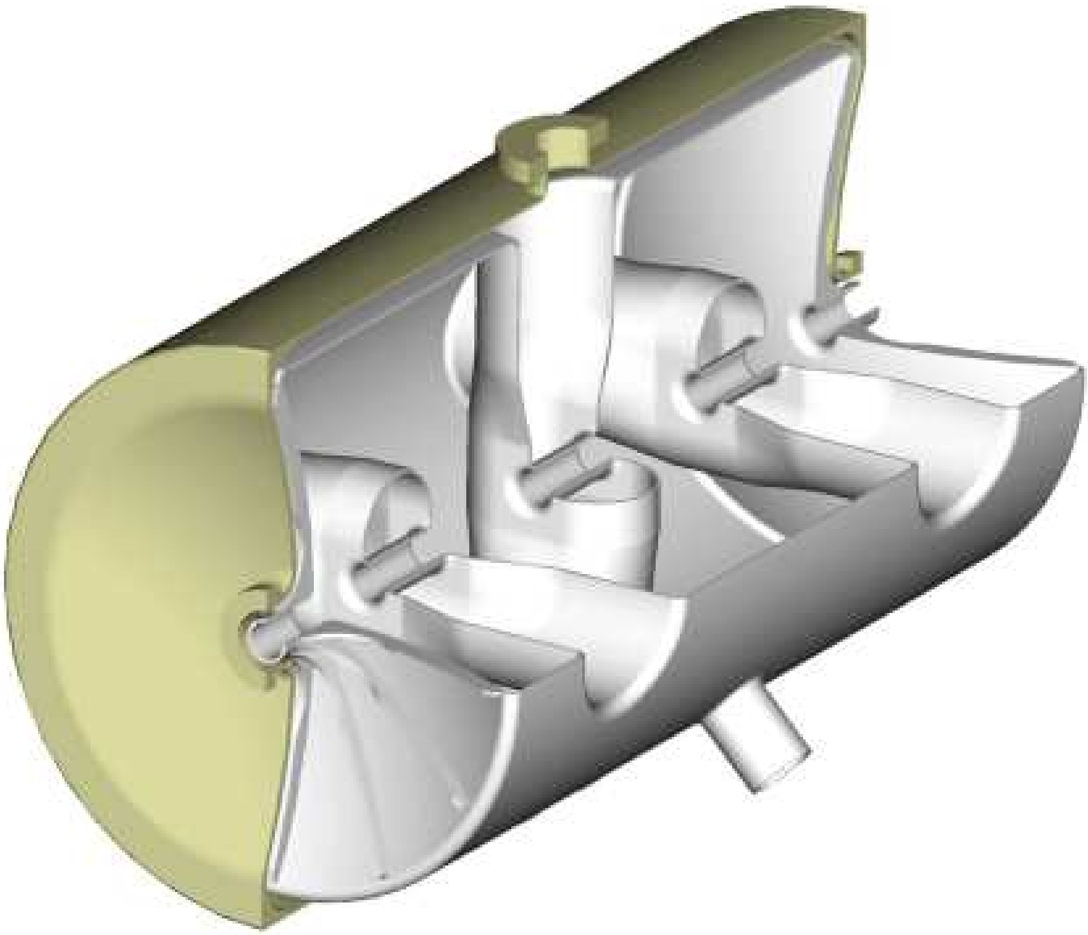


In tests at ANL a 350 MHz, beta .4 spoke cavity has been operated CW at Ea = 7 MV/m (28 MV/m Epeak) for 1 month

In the past 18 months, high-pressure water rinsing, at several different laboratories, has produced increased gradients in drift-tube cavities



Preliminary designs for triple-spoke cavities for the RIA driver



$ß_{GEOM}$	0.48	0.62
$L_{EFFECTIVE}$	65 cm	85 cm
Frequency	345 MHz	345 MHz
QR_S	92	103
€		
at 1 MV/m		
E_{PEAK}	3.0	3.1
B_{PEAK}	90	88
RF Energy	356 mJ	582 mJ

Why triple-spoke cavities?

- **Fewer types (2) and a smaller total number of cavities are required, reducing costs and the length of the linac tunnel.**

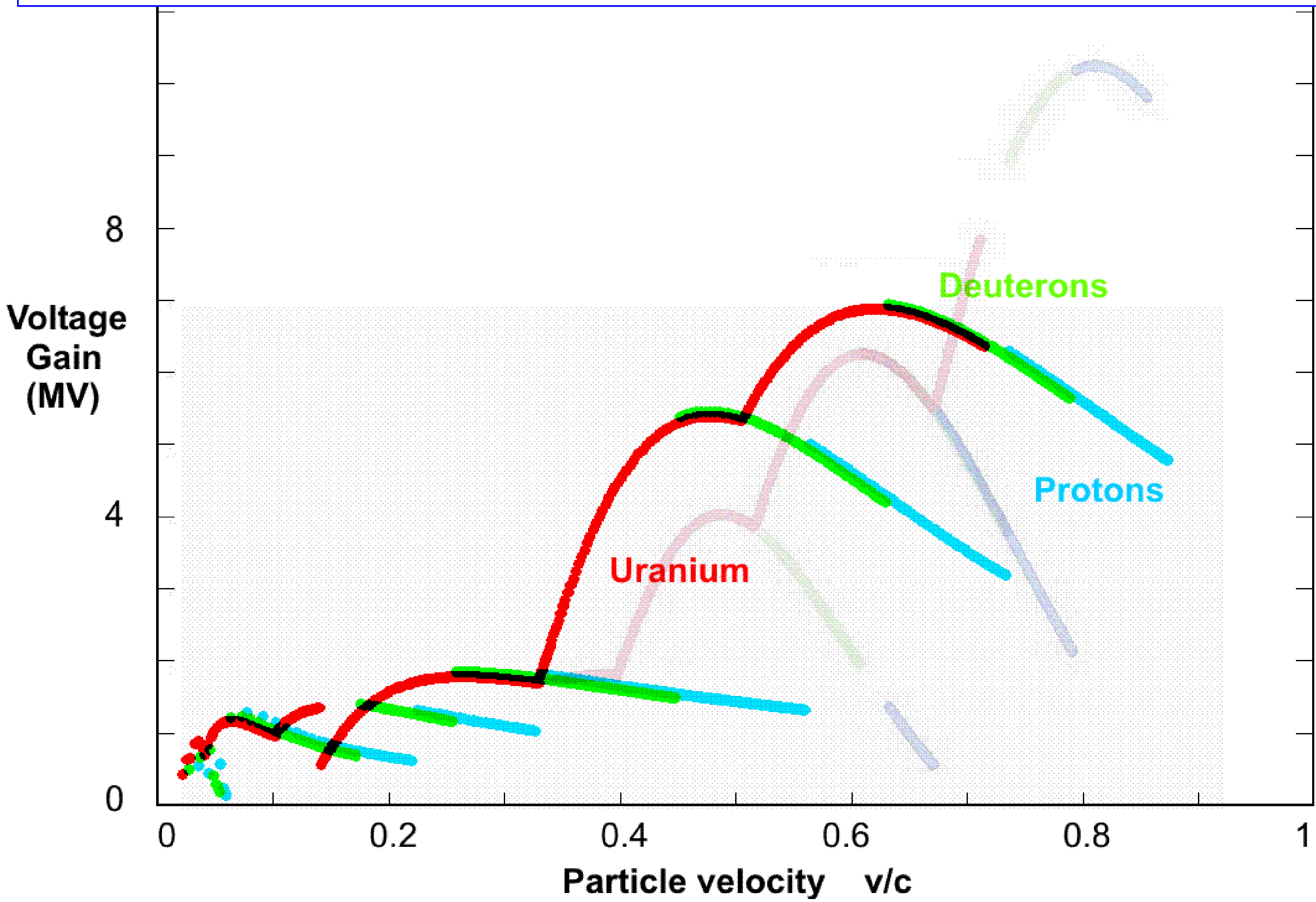
- **The cavities can operate at a higher temperature, reducing the complexity of the cryogenic system and the total cryogenic load.**

- **Beam quality is improved, because of increased longitudinal acceptance and the elimination of a frequency transition**
- **The possibilities for beam loss and activation are reduced.**

- **Output energies for the lighter ions are increased, protons by more than 100 MeV, by the broader velocity acceptance of the triple-spoke geometry.**

- **For $\beta \leq 0.6$, the spoke-loaded structure has superior mechanical stability**

Voltage gain per cavity vs. velocity for 345 MHz spoke cavity option



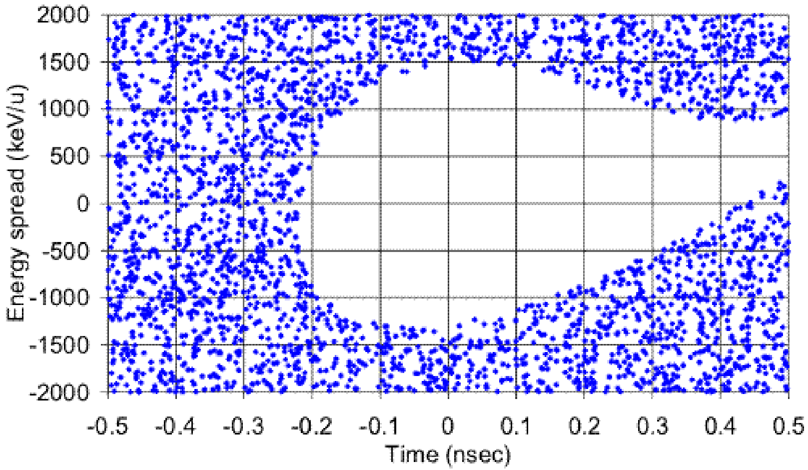
Comparison of Beam Output Energies for Elliptical-cell and spoke cavity options

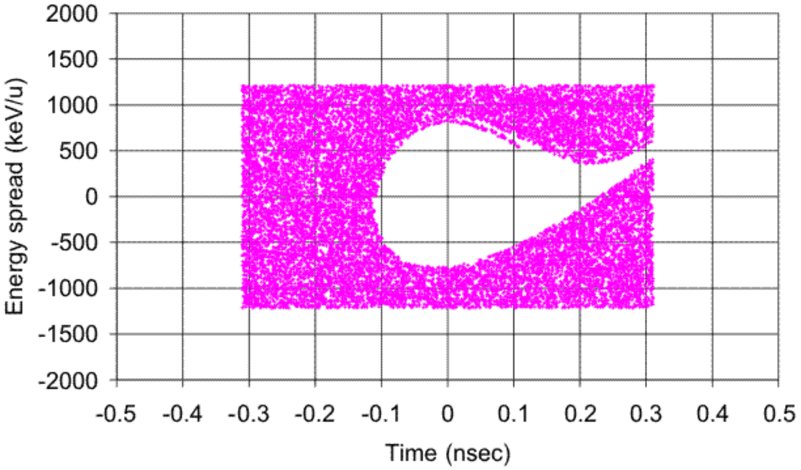
Species	Input Q	Strip	Output Energy (MeV/A)	
			E - 6 Cell	3 Spoke
H	1	none	893	988
^{3}He	2	none	707	737
D	1	none	587	595
^{136}Xe	18	twice	461	451
^{238}U	29	twice	403	404

A low frequency option for the high-energy section – 345 MHz spoke cavities

	Elliptical-Cell		Triple-Spoke	
	Beta	# Cav	# Cav	Beta
	0.031	5	5	0.031
	0.061	32	32	0.061
	0.151	30	30	0.151
	0.263	88	100	0.263
	0.393	72	**	**
Subtotal		227	167	DT Cavities
	0.490	58	66	0.475
	0.610	80	104	0.617
	0.810	28	**	**
Subtotal		166	170	Hi-beta Cavities
Total		393	337	Cavity Count

Longitudinal Acceptance for the 805 MHz and 345 MHz Options





345 MHz Spoke cavities increase the longitudinal acceptance four-fold

805 MHz Elliptical-cell cavities

Discussion on "RIA Project:Driver Linac Overview" by Ken Shepard

Ken presented a number of reasons, why spokes will be superior to elliptical cavities at medium βs (around 0.5) for the RIA project. The question was raised if there are any reasons to stick with elliptical cavities for any future projects in this beam velocity range. Ken answered that he does not see any reasons for this, he even thinks SNS, if it would be designed today, should use spokes in this range.

Related to presented cavity shapes it was asked why the new multi-gap spoke resonators for RIA use racetrack cross-sections at the aperture, while the previous shorter designs used round spokes. Ken answered that he thought that the non-homogeneous spokes would be more complex in fabrication. Recent thoughts about this convinced him that there are no differences in manufacturing complexity.

It was pointed out that LANL saw differences in conditioning and multipacting behavior between the ANL cavities with round spokes (short conditioning time) and the LANL spoke with a racetrack cross-section (long conditioning time). Ken's experience showed conditioning times from 10s of minutes to 18 hours for his spoke resonators over the years. He believes that multipacting is not understood yet and should be tackled in the near future.

Status on Spoke Resonators R&D for two European Projects: XADS and Eurisol

T. Junquera, IPN (CNRS) Orsay, France

The IPN (Institut de Physique Nucleaire-CNRS) is currently working on the design of linear accelerators for two european projects: XADS and Eurisol. XADS is an eXperimental Accelerator Driven System for nuclear waste transmutation. Eurisol is a nuclear physics facility for radioactive beams using the ISOL technique. Both projects have received the support of the European Commission, coordination structures and design working groups are currently at work with an active participation of many european laboratories and industrial firms. R&D activities have progressed in several laboratories and a coordinated R&D program is planned for the next four years.

The proposed characteristics of these accelerators are very close: proton beams with an energy in the range of 600 MeV – 1 GeV, an intensity in the range of 5 – 10 mA, and CW operating mode. The present proposal is a linear accelerator using superconducting elliptical cavities for the high energy sections (> 100 MeV). For the intermediate energy sections of the accelerator (5/10 MeV to 100 MeV), the IPN-Orsay proposes to use spoke resonators. A study program was decided last year. Detailed studies on beam dynamics, RF structure, and mechanical design have been developped in the last period. A first spoke Nb prototype (β=0.35) has been recently constructed, and the test program has recently started. Several other resonators with β values in the range 0.15 to 0.35 are planned in the short term.

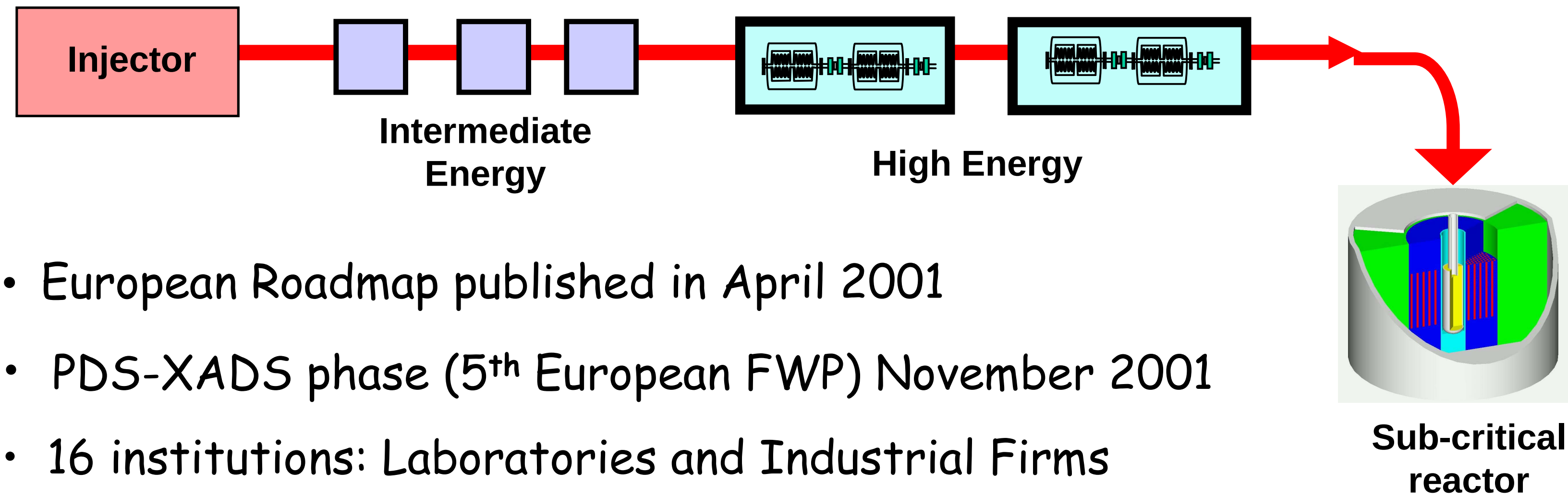
Workshop on Advanced Design of Spoke Resonators

Los Alamos. October 7-8, 2002

"Status on Spoke Resonators R&D for two European Projects: XADS and Eurisol"

T. Junquera , IPN (CNRS) Orsay, France

XADS Project



- European Roadmap published in April 2001
- PDS-XADS phase (5th European FWP) November 2001
- 16 institutions: Laboratories and Industrial Firms
- R&D Program supported in the 6th E.FWP (2003...2006)
- Goals:
  - ❑ **Accelerator preliminary design: 600 MeV, 10 mA max (6 mA in the target)**
  - ❑ **Accelerator architecture optimization**
  - ❑ **Hardware development and tests (demonstrations)**
  - ❑ **Reliability studies**
- Decision for the construction: 2006

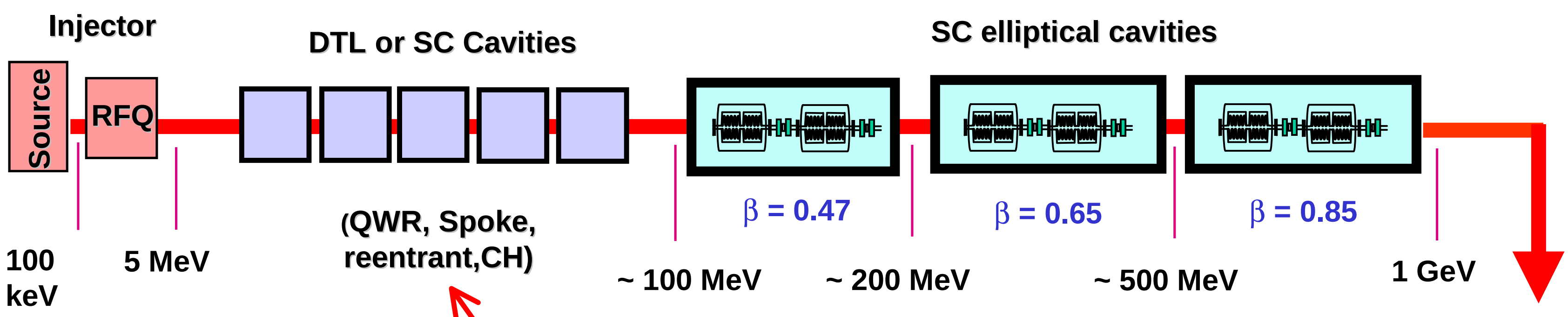
European Isotope Separation On-Line Radioactive Nuclear Beam Facility

- The EURISOL project is one of the Research and Technical Development (RTD) projects in Nuclear Physics selected for support by the EU under the 5th Framework. The project is aimed at completing a preliminary design study of the next-generation European ISOL radioactive nuclear beam (RNB) facility.

- Collaboration of 11 Laboratories (5 working groups and a steering committee)
  - Key experiments (B. Jonsson)
  - **Driver accelerator (A. Mueller): protons 1 GeV, 5 mA (CW)**
  - Instrumentation for experiments (J. Aysto)
  - Isotope separation and post acceleration (M- H. Moscatello)
  - Targets and ion sources (H. Ravn)

- Time and financial perspectives
  - R&D in the 6th European FWP (2003 ... 2006)
  - EU could finance 50% of the project study and 10% of the facility
  - **Final report of present "pre- study" for the end of 2002**
  - Physics after 2010

Linear Accelerator Generic Scheme



Interest of Spoke Resonators :

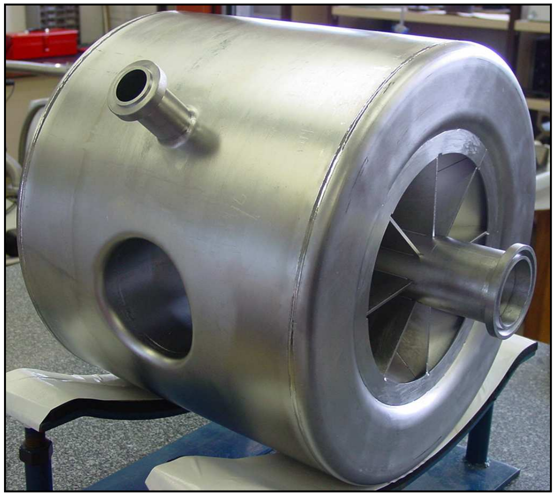
- Large beam aperture
- Mechanical stability
- Negligible steering effects
- Modularity : Independent RF powering and control

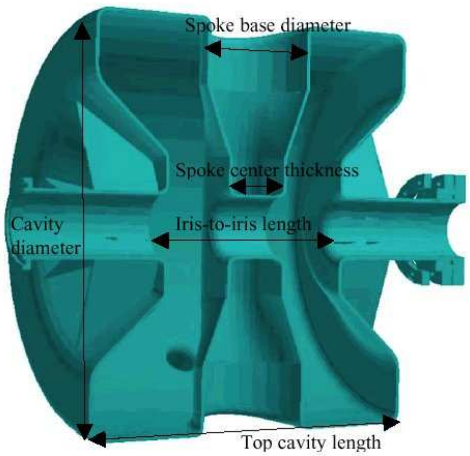
Proposed Intermediate Sections using 2 gaps Spoke Resonators

Beam intensity: 10 mA CW	β=0.15 section	β=0.35 section
Energy range (MeV)	5 - 17	17 - 95
# Cavities	34	62
# Cavities per focusing lattice	1	2
Energy gain per real meter (MeV/m)	0.06 -0.38	0.31 - 1.58
Beam loading RF power (kW/cavity)	0.8 - 5.0	4.1 - 15.0
Overall length (m)	44.2	58.9

Talk of J.L. Biarrotte

First Nb Prototype β = 0.35 (fabricated by CERCA-France)





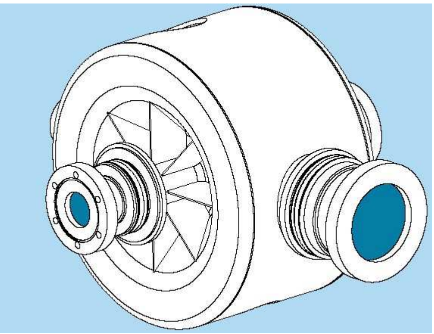
- Delivered in July 2002
- RT tests underway
- 4K tests November 2002

Talks:

- G. Olry : Design
- J. Lesrel : Fabrication
- S. Bousson : Processing

Mid-term R&D Program on Spoke Resonators

- Optimization of the Intermediate Sections Architecture
- Second Nb prototype : β=0.15
  - Design is near completion
  - Preparation of manufacturing aspects (CERCA)



- Collaboration with LANL on a new prototype
- Power Coupler studies
- Cryomodule studies
- Power tests at 4 K

Discussion on "Status on Spoke Resonators R&D for two European Projects: XADS and Eurisol" by Tomas Junquera

The designs for the two projects use 2-gap spoke resonators at $\beta=0.15$. It was pointed out that this is a solution with a poor real estate gradient. It was suggested to treat this lowest β region differently and utilize high velocity acceptance structures only at the higher β of 0.35. For the lower velocity multigap spokes or other rigid structures like the CH structure should be considered. Tomas agreed that the $\beta=0.15$ region needs more study.

Electrodynamics & Mechanics of Multigap Low-beta SC Structures

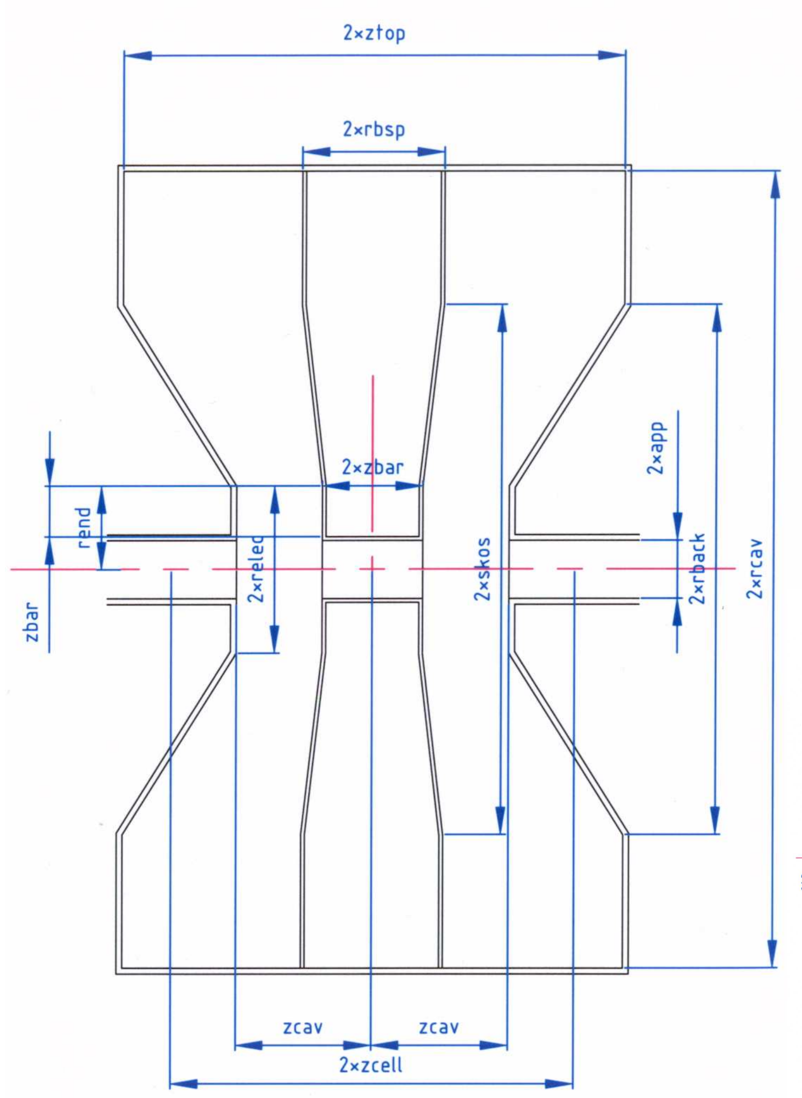
E. Zaplatin, Forschungszentrum Juelich

The basic ideas of multigap spoke cavity geometry optimisation in terms of electrodynamics and mechanics are presented. We investigate structures for two most used frequencies 700 and 350 MHz for different beta values. Some specific problems of cavity production are discussed.

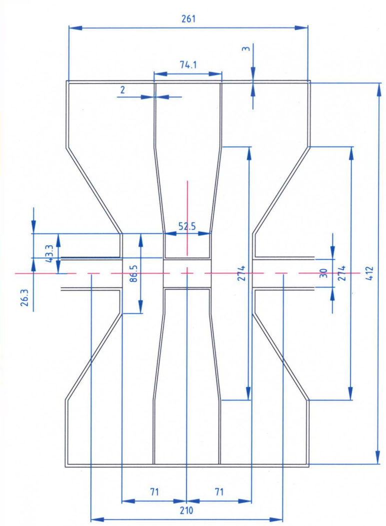
ELECTRODYNAMICS & MECHANICS OF MULTYGAP LOW-β SC STRUCTURES

Evgeny N. Zaplatin

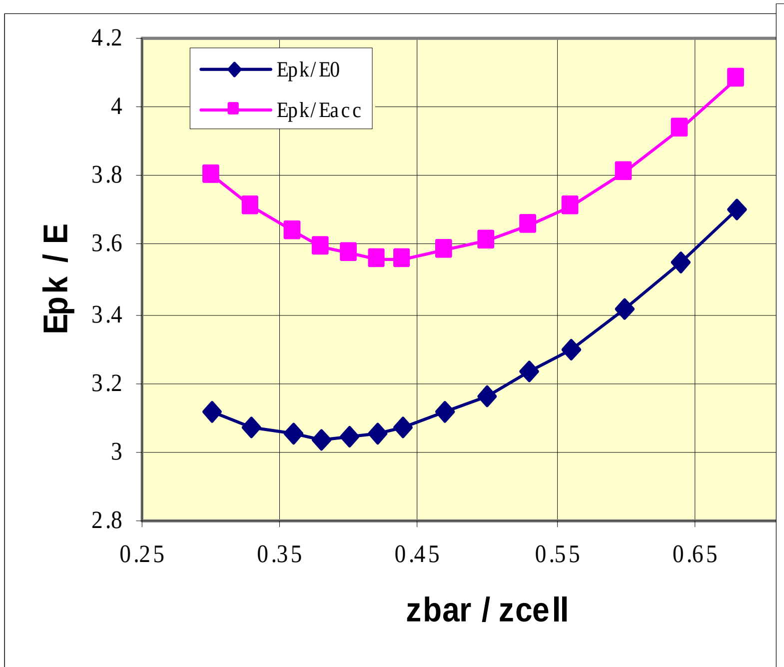
SPOKE CAVITY GEOMETRY

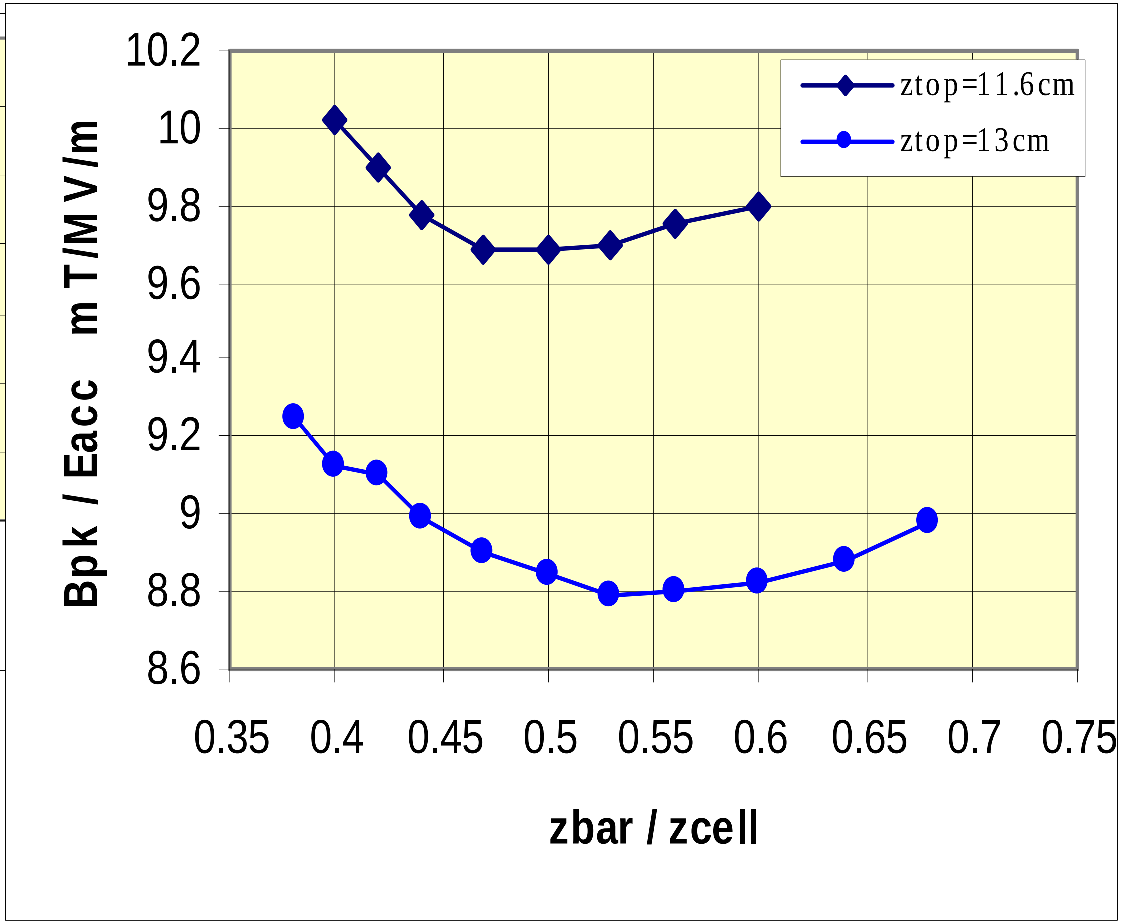


spoke 320-0.224-0.50



SPOKE CAVITY (320 MHz , β=0.224)

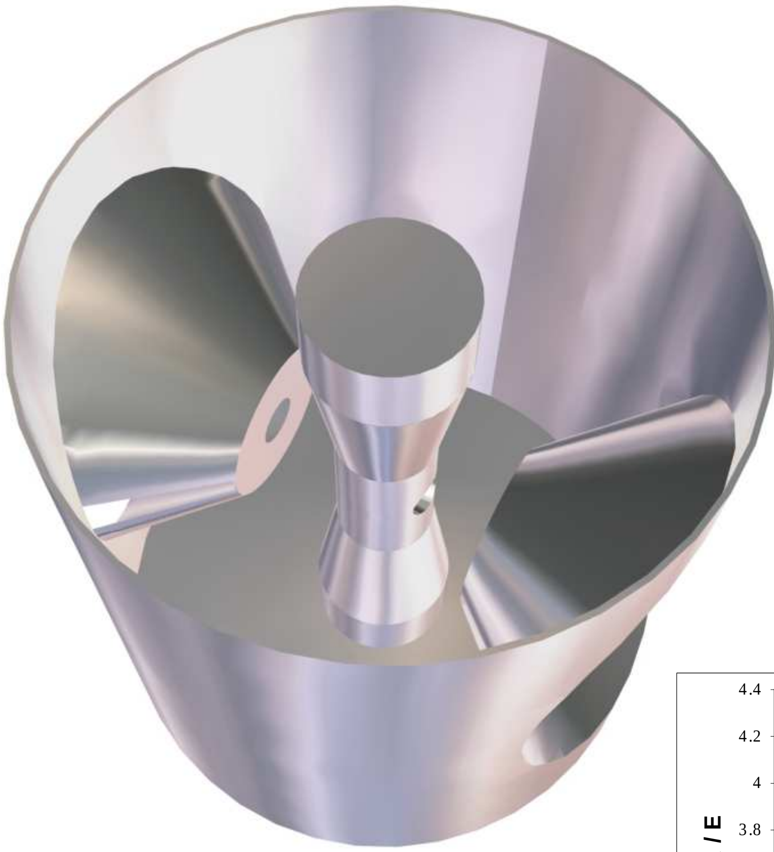


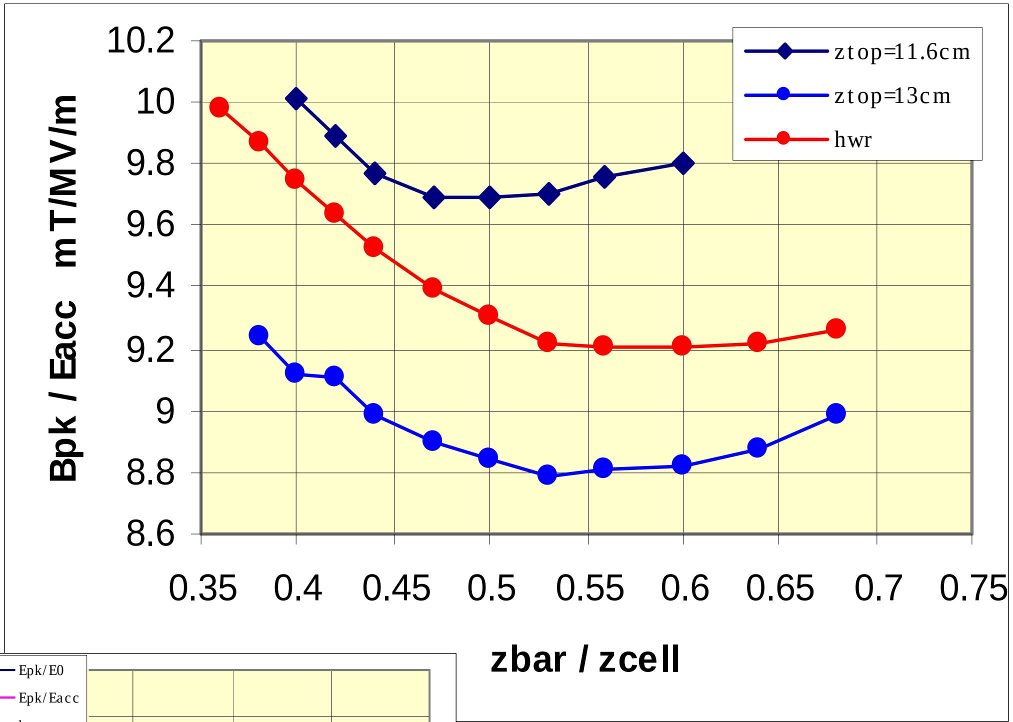


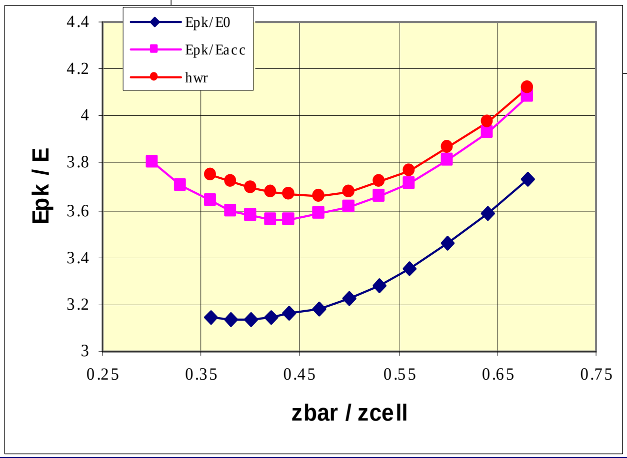
ztop=11.6cm @ B_{pk} = 66.(6) mT => E_{acc} = 6.88 MV/m (E_{pk} = 24.5 MV/m)

ztop=13.0cm @ B_{pk} = 66.(6) mT => E_{acc} = 7.58 MV/m (E_{pk} = 28 MV/m)

HALF-WAVE COAXIAL CAVITY (320 MHz , β=0.224)







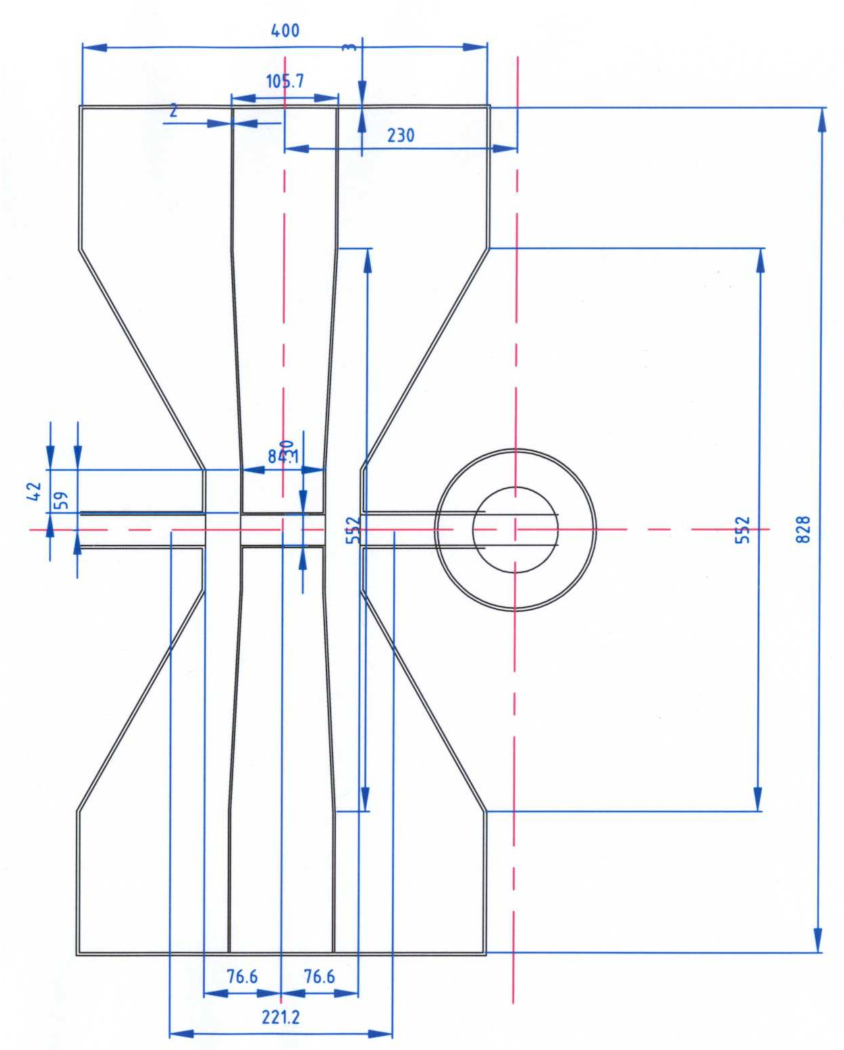
ztop = 13 cm

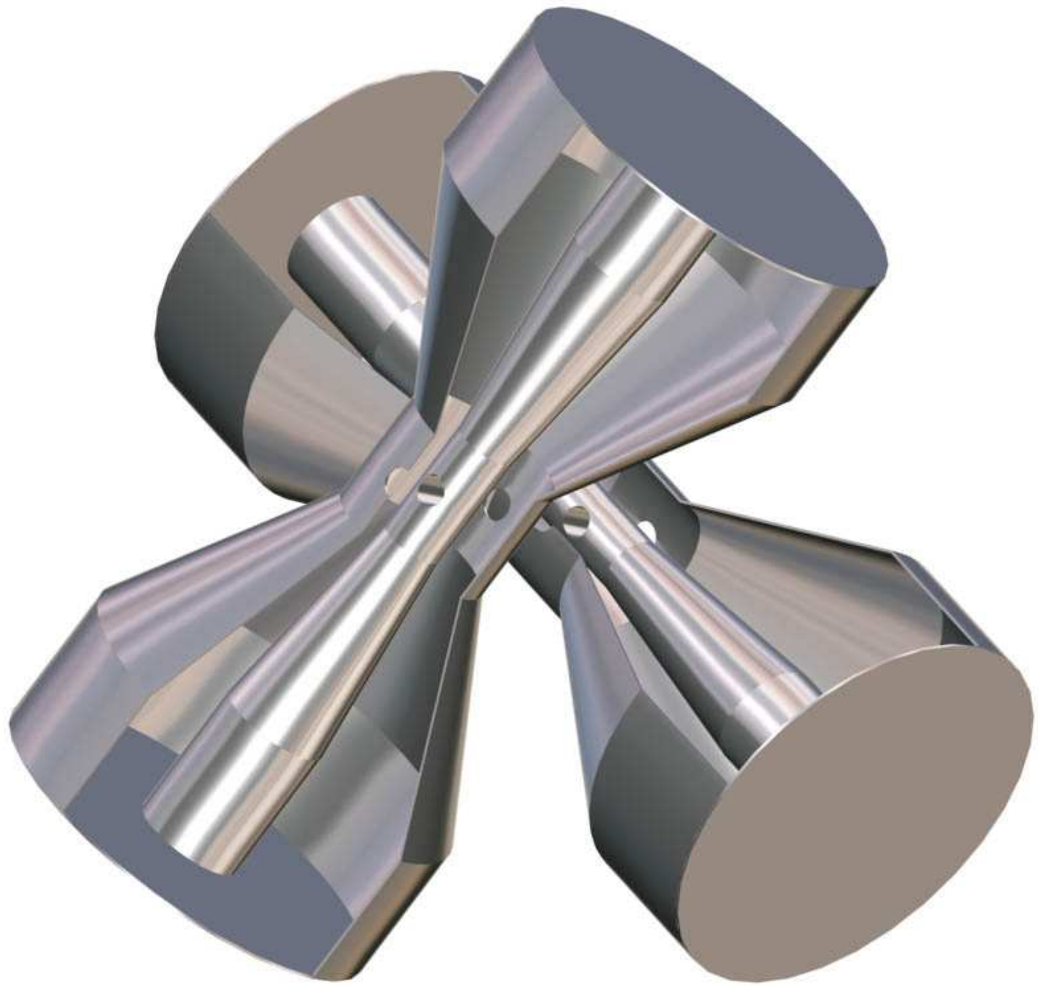
@ B_{pk} = 66.(6) mT =>

E_{acc} = 7.25 MV/m

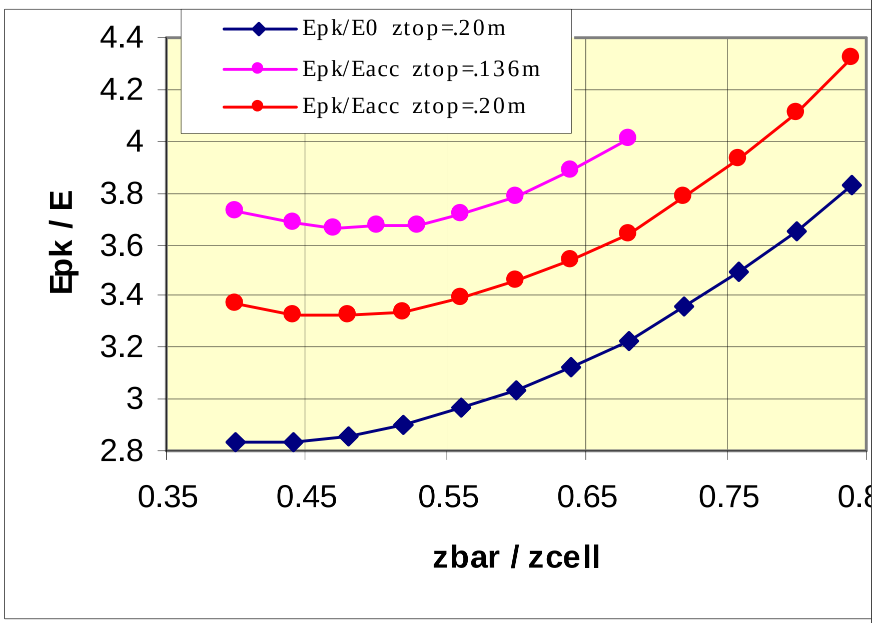
(E_{pk} = 28 MV/m)

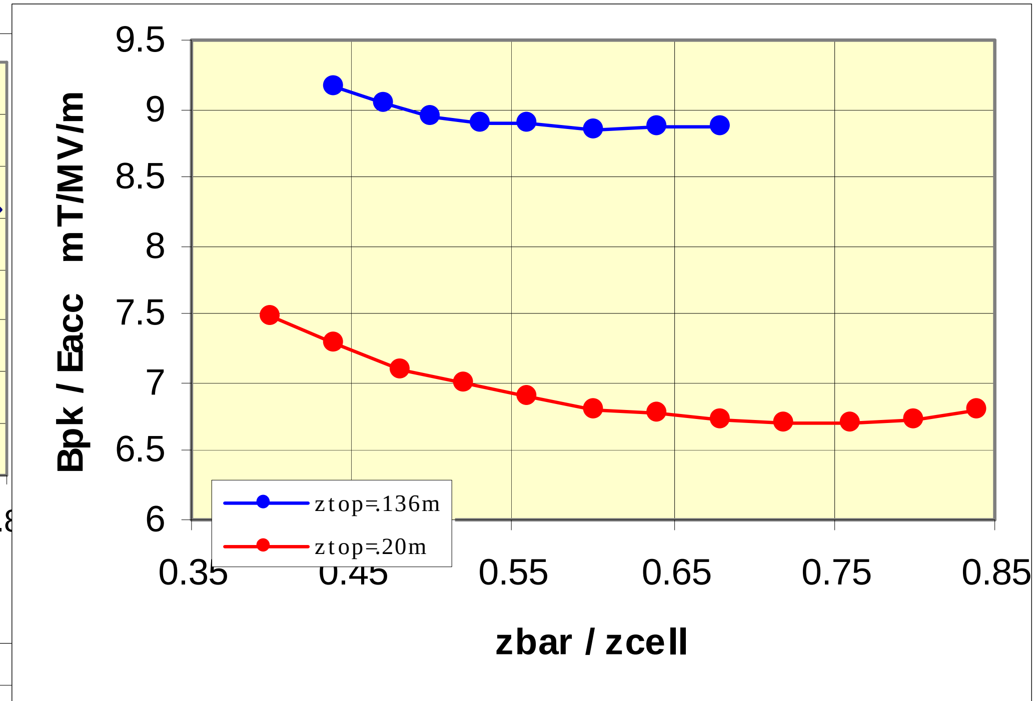
HALF-WAVE COAXIAL CAVITY (160 MHz , β=0.118)

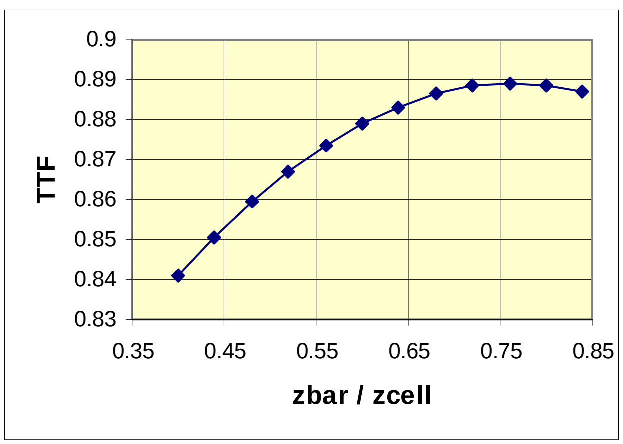


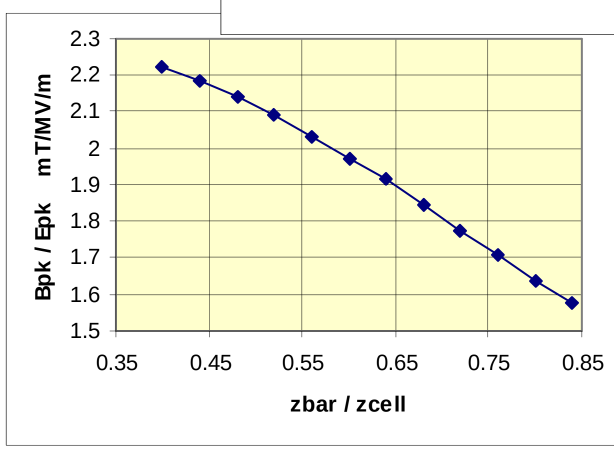


HALF-WAVE COAXIAL CAVITY (160 MHz , β=0.118)









zbar/zcell = 0.72

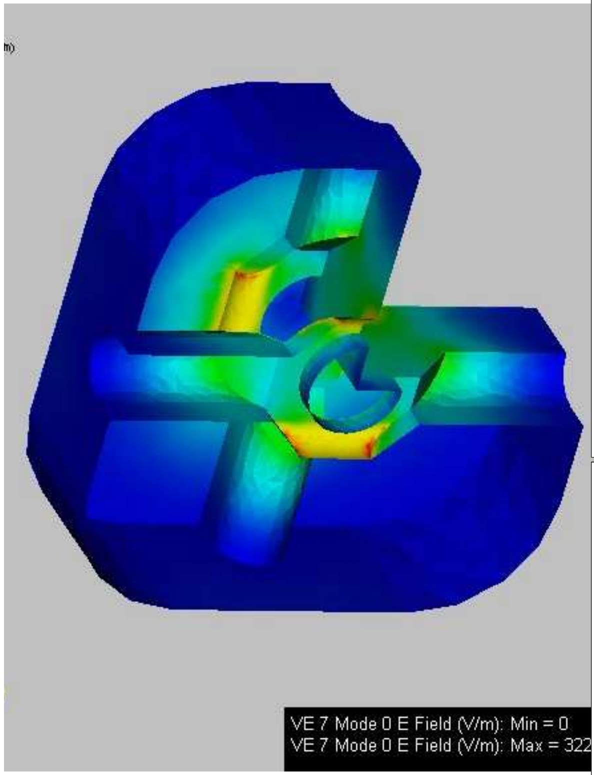
ztop = 20.0 cm

@ B_{pk} = 66.(6) mT =>

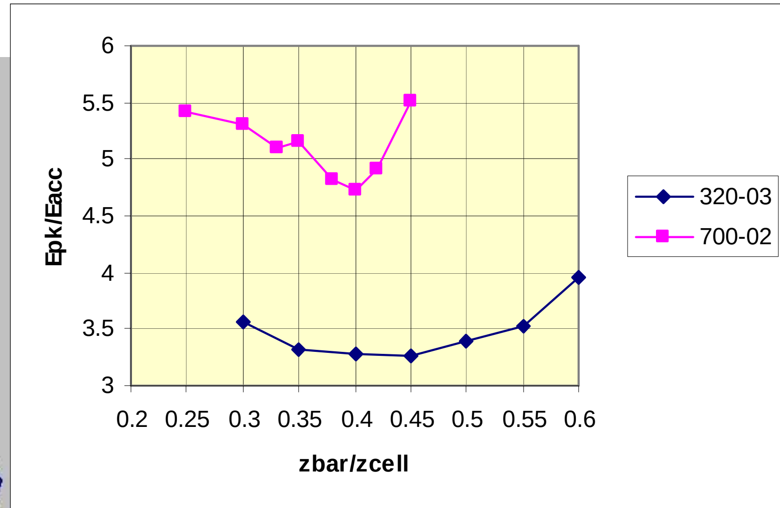
E_{acc} = 9.94 MV/m

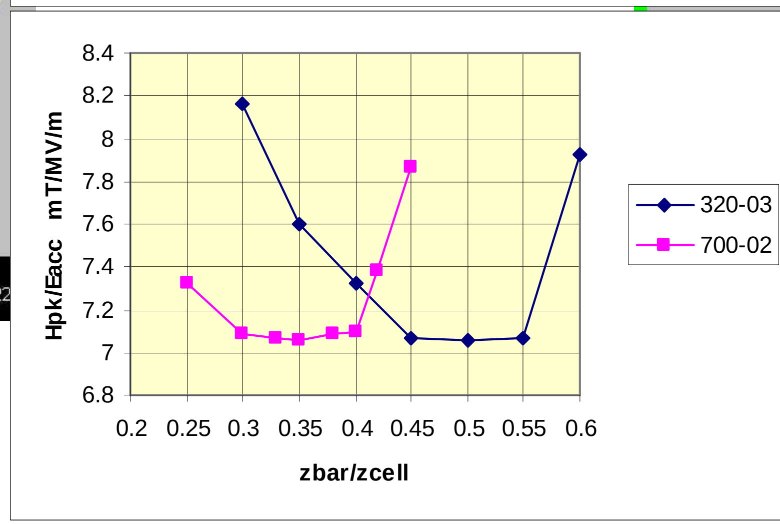
(E_{pk} = 37.6 MV/m)

E_{pk} & B_{pk} OPTIMISATION BY ACC. GAP GEOMETRY

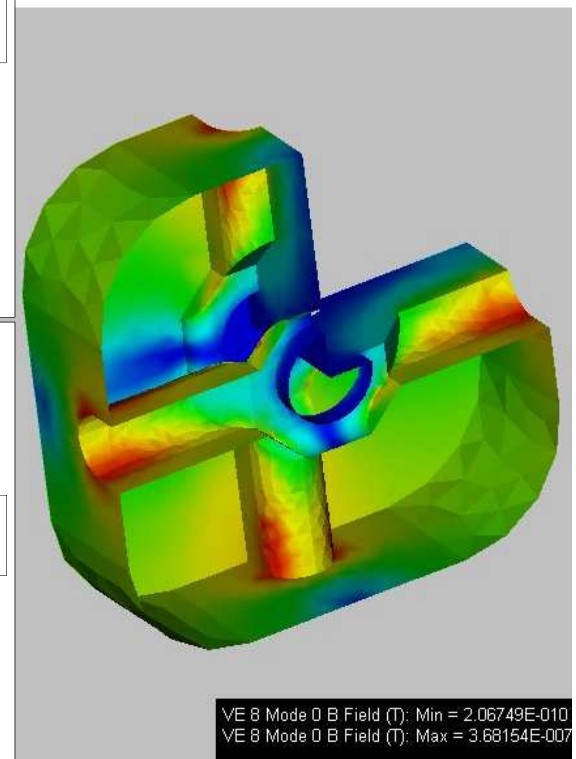


Electric RF field distribution

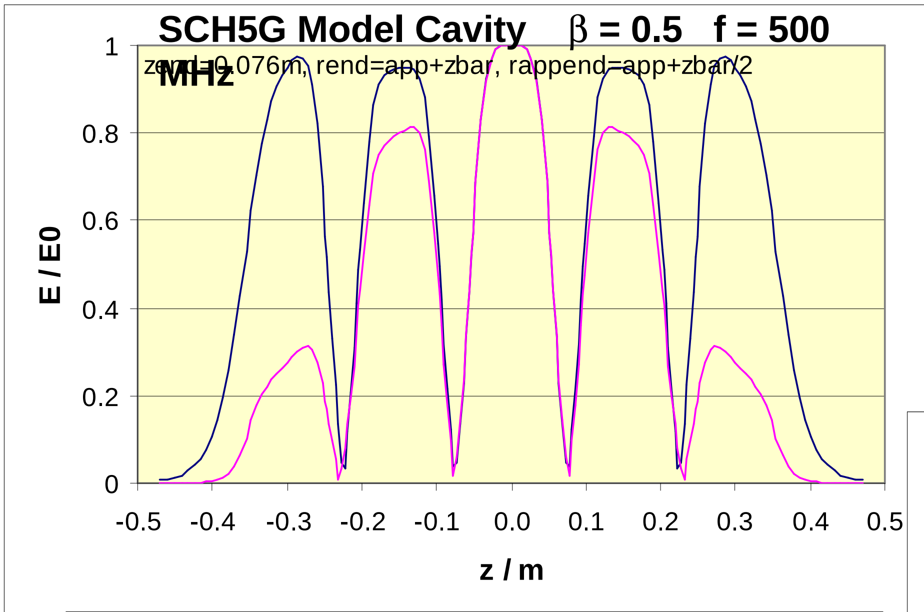


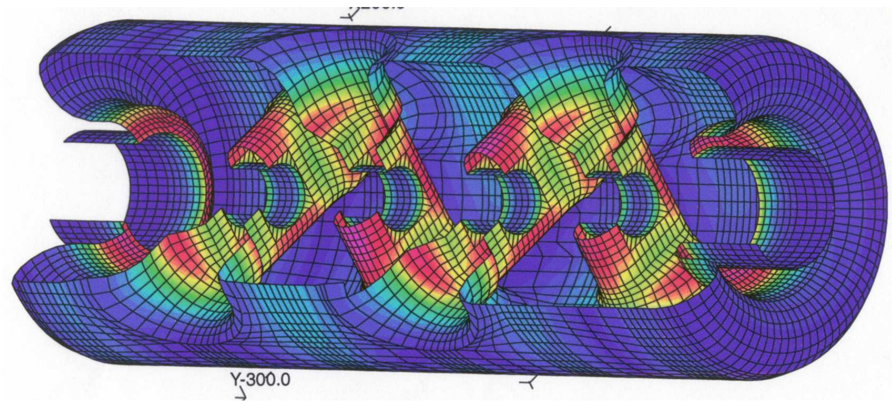


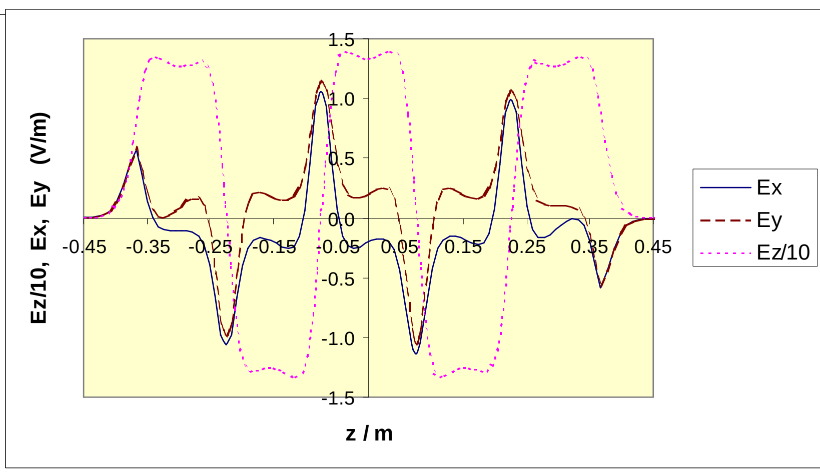
Magnetic RF field distribution

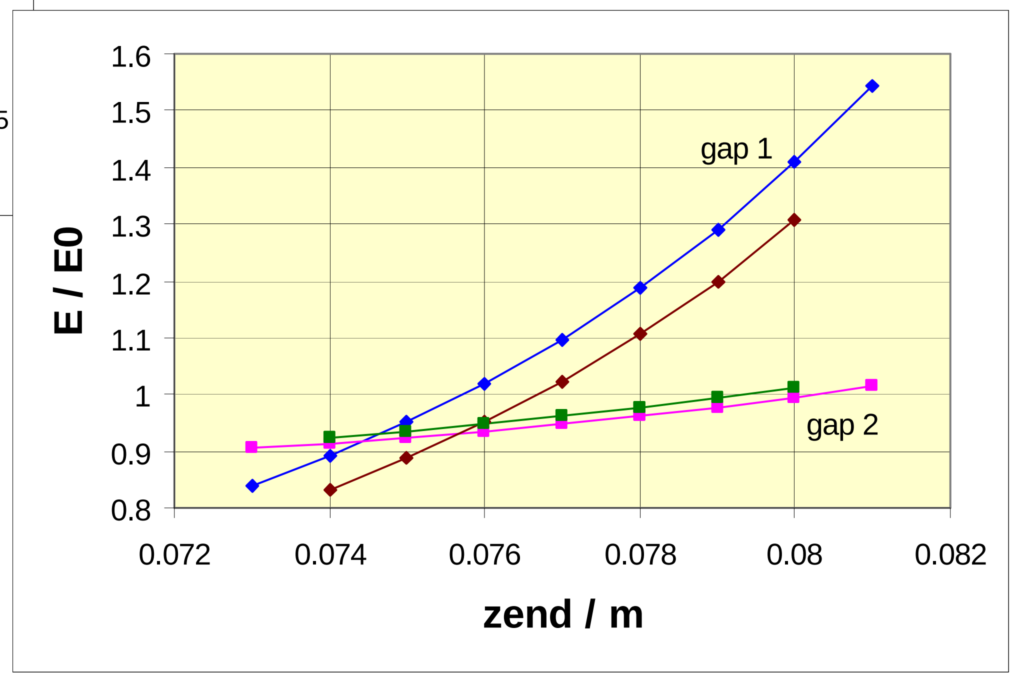


E-FIELD PROFILE OPTIMISATION BY END ELECTRODE LENGTH CHANGE

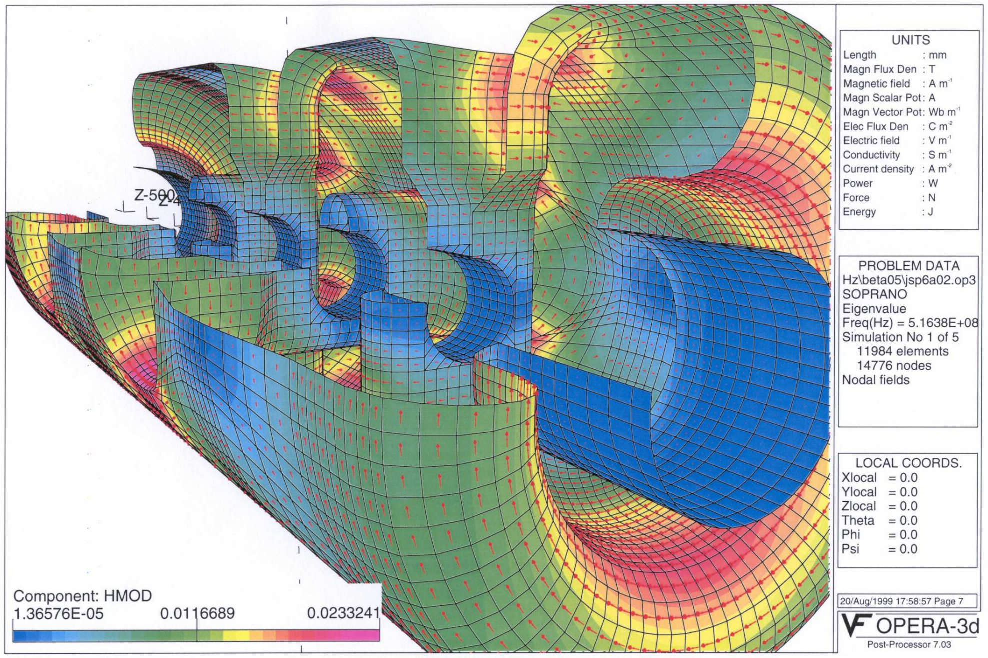


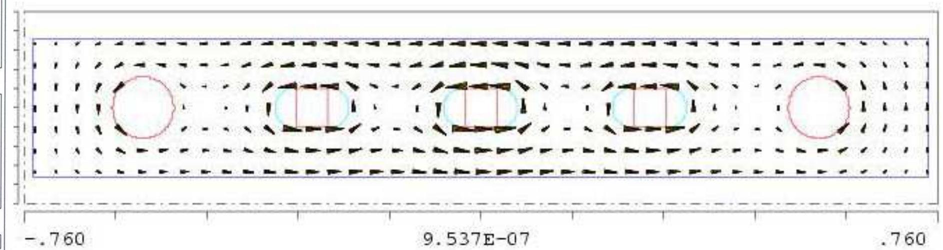


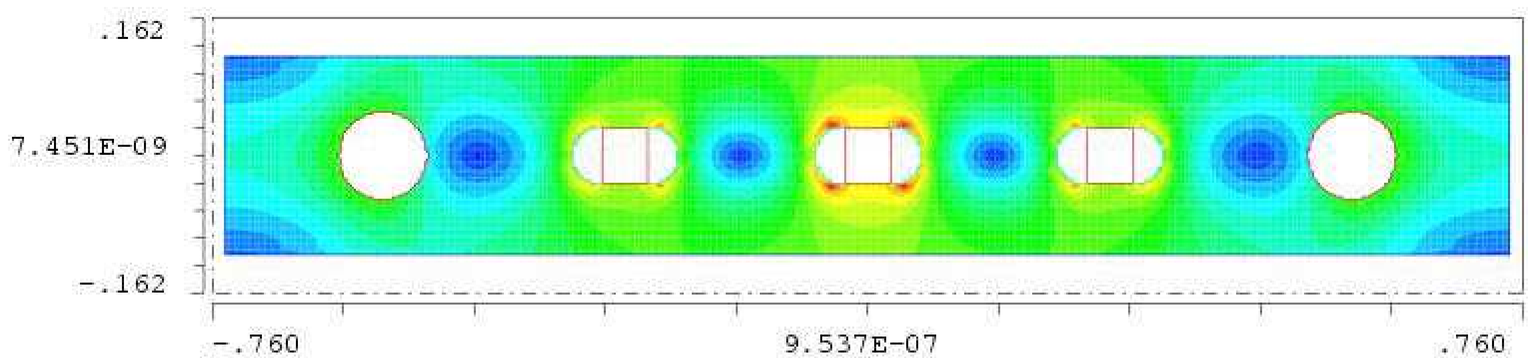




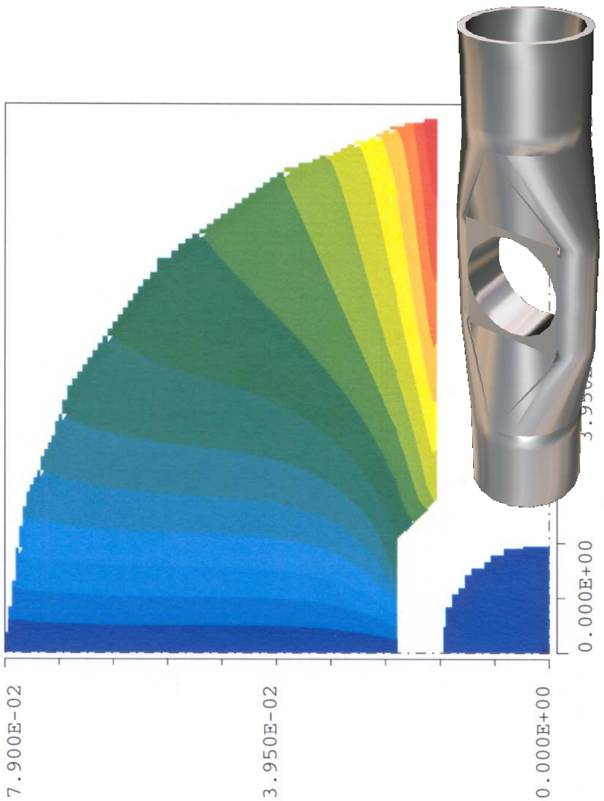
SC H-CAVITY RF MAGNETIC FIELD DISTRIBUTION

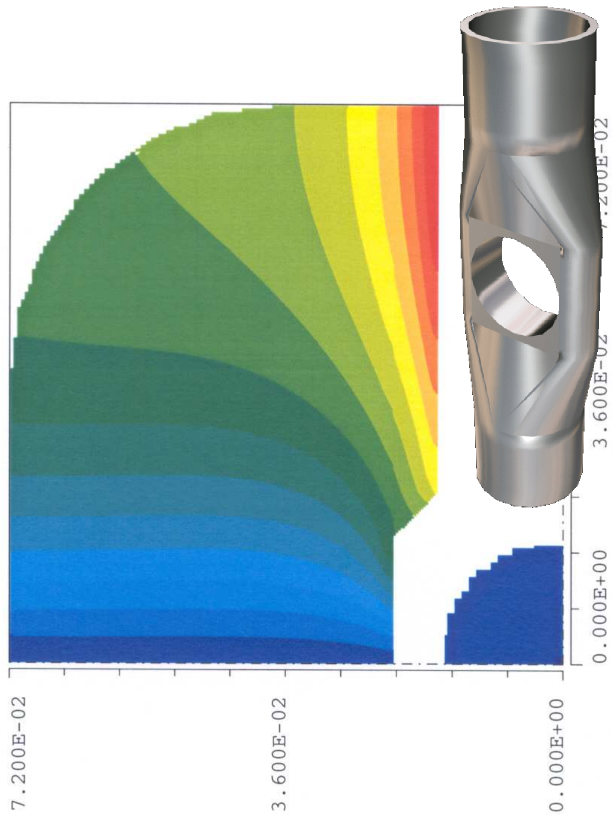


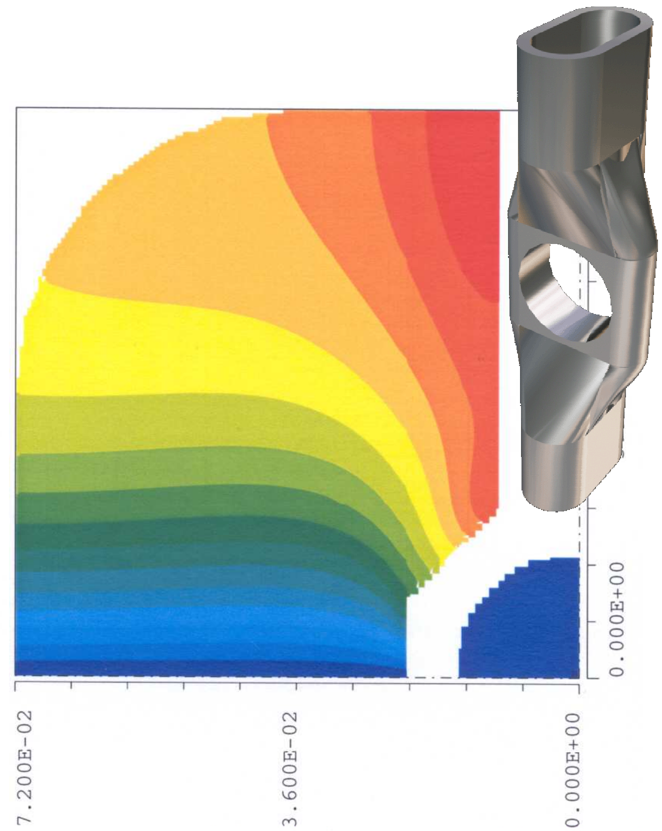




B_{pk} OPTIMISATION BY CROSS CAVITY GEOMETRY







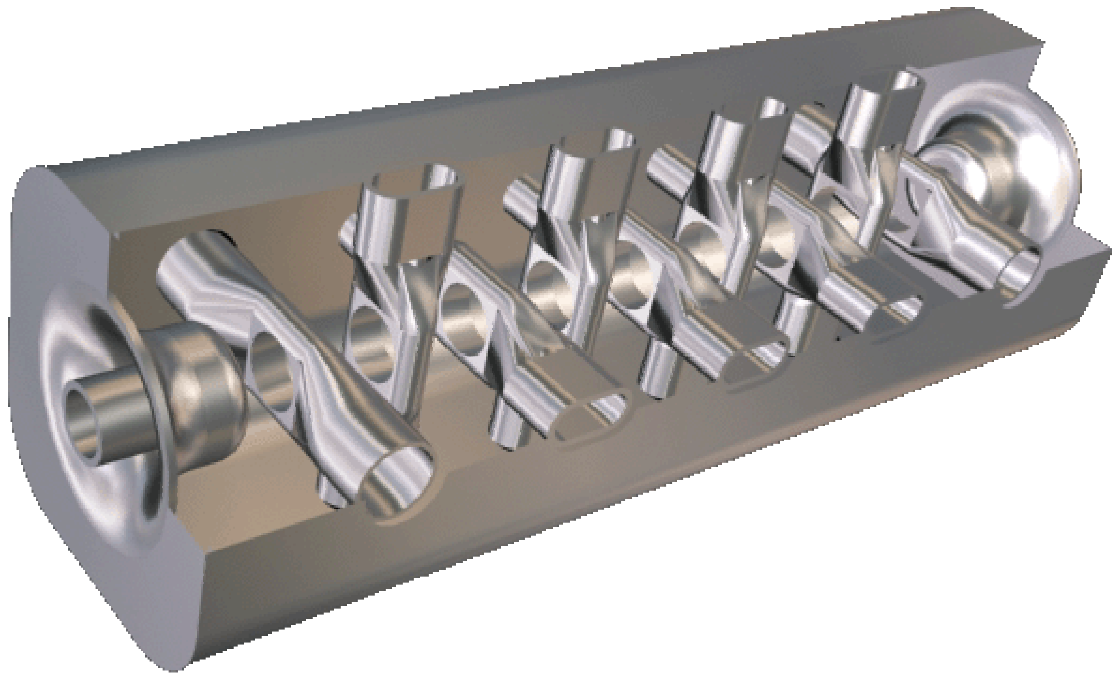
B_{pk}/E_{acc} = 9.20 mT/MV/m

B_{pk}/E_{acc} = 8.17 mT/MV /m

B_{pk}/E_{acc} = 7.06 mT/MV /m

SC H-CAVITY (700 MHz , β=0.2)

frequency	MHz	700
$\beta = v/c$		0.2
R_{cav}	cm	7.15
L_{cav}	cm	48.5
app. R_i	cm	1.5
cell	cm	4.283
wall thickness	mm	2.0 / 1.0
ttf		0.778
E_{pk} / E_{acc}		5.10
B_{pk} / E_{acc}	mT/MV/m	7.06
B_{pk} / E_{pk}	mT/MV/m	1.38

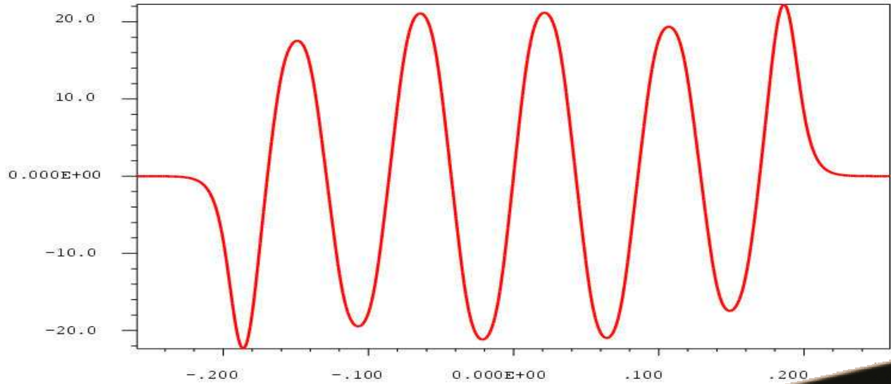


SCH-CAVITY PARAMETRS

frequency	MHz	700	700	700	320	352
$\beta = v/c$		0.2	0.4	0.55	0.22	0.1
R_{cav}	cm	7.15	9.10	9.20	15.15	11.3
app. R_i	cm	1.5	1.5	1.5	1.5	1.5
cell	cm	4.283	8.565	11.78	10.3	4.26
cav. length	cm	48.5	87.5		113.5	53.4
No. of gaps		10	10	10	10	10
ttf		0.778	0.778	0.783	0.888	.813
E_{pk}/E_{acc}	MV/m	5.10	3.88	3.79	4.61	5.61
B_{pk}/E_{acc}	mT/ (MV/m)	7.06	8.03	9.76	6.42	3.85
B_{pk}/E_{pk}	mT/ (MV/m)	1.38	2.07	2.58	1.39	0.69

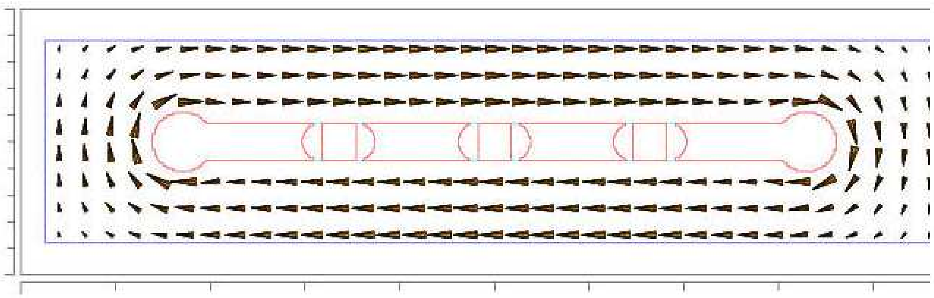
10-GAP SC H-CAVITY (320 MHz , β = 0.3)

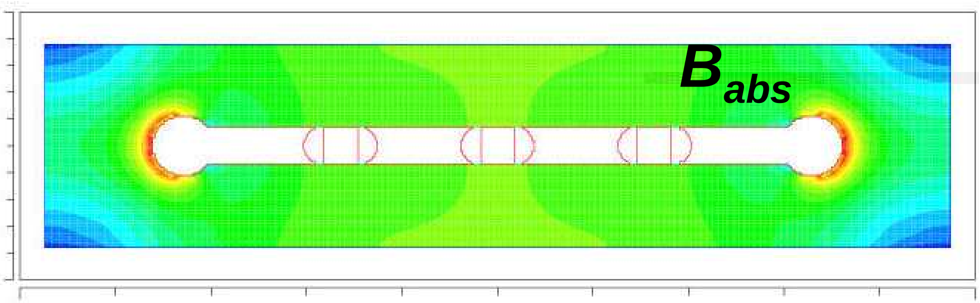
Bars



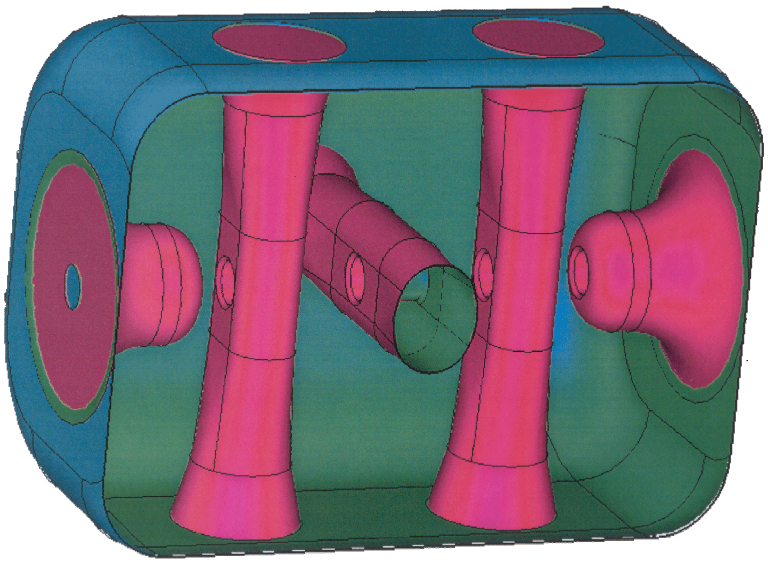
E_z along beam path

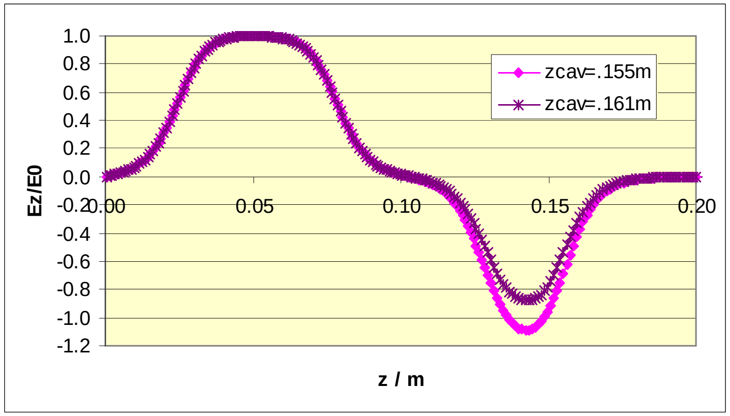
RF magnetic field distribution



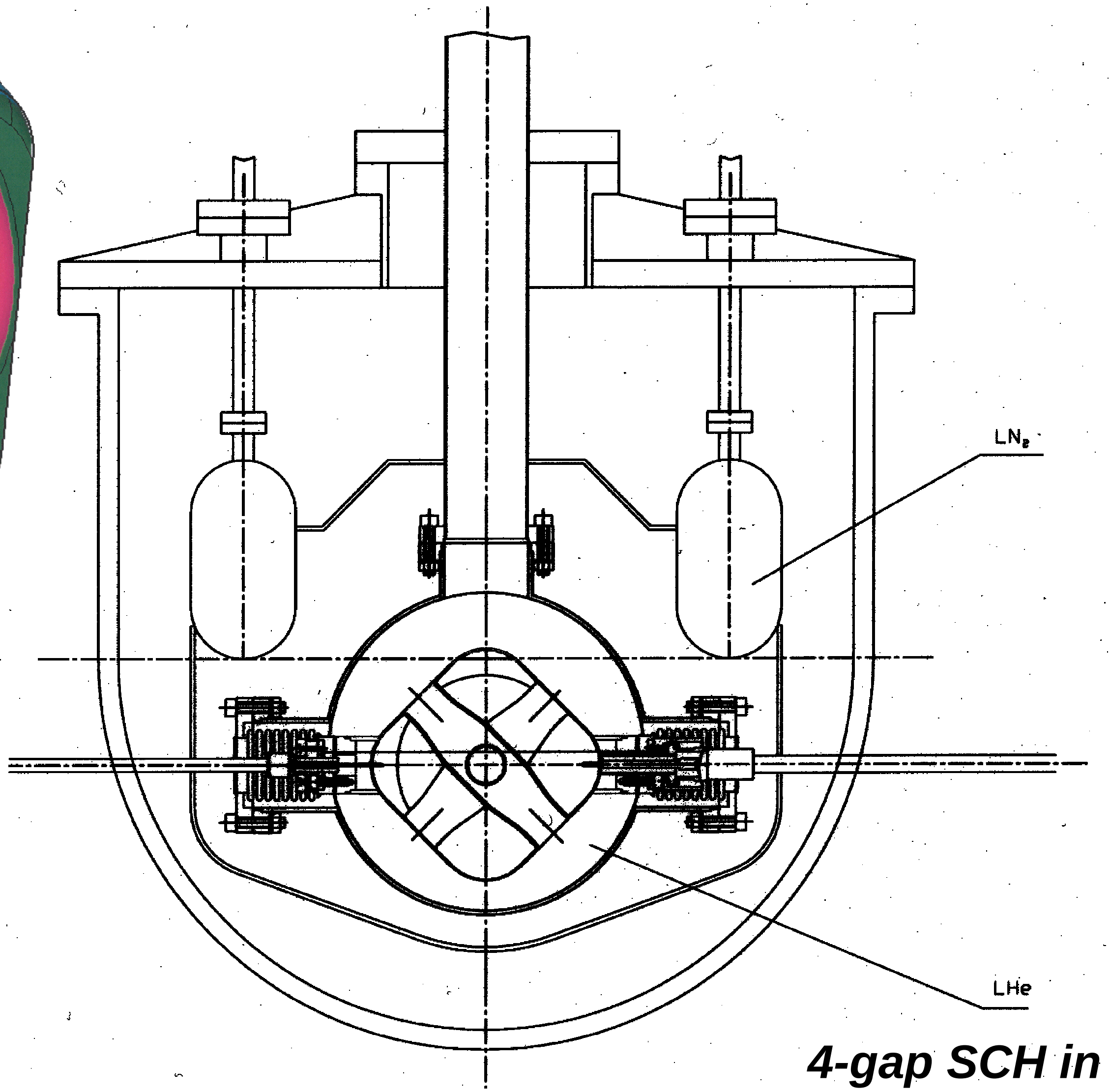


4-GAP SC H-CAVITY (320 MHz , β=0.2)



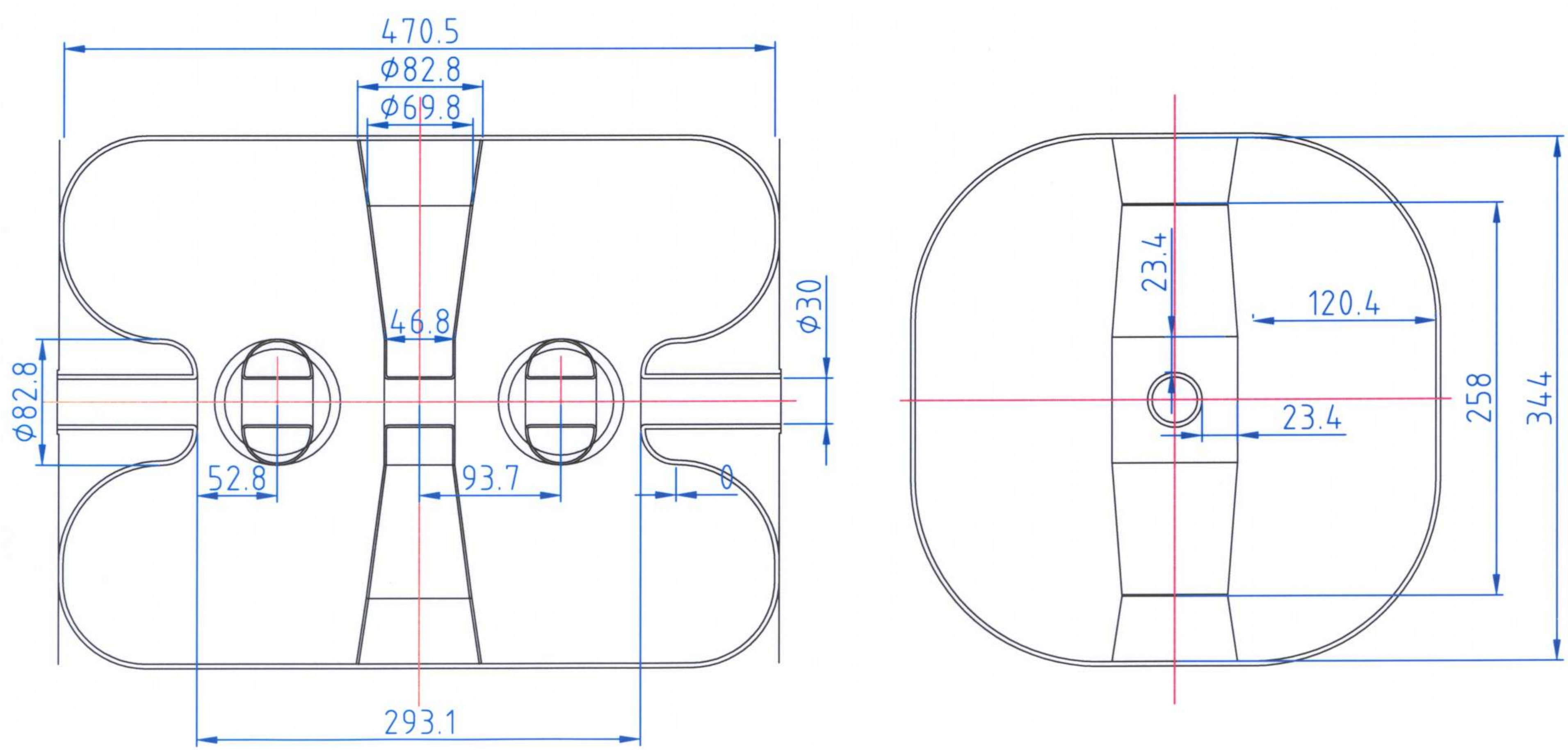


E_z field in 4-gap SCH



4-gap SCH in Cryostat

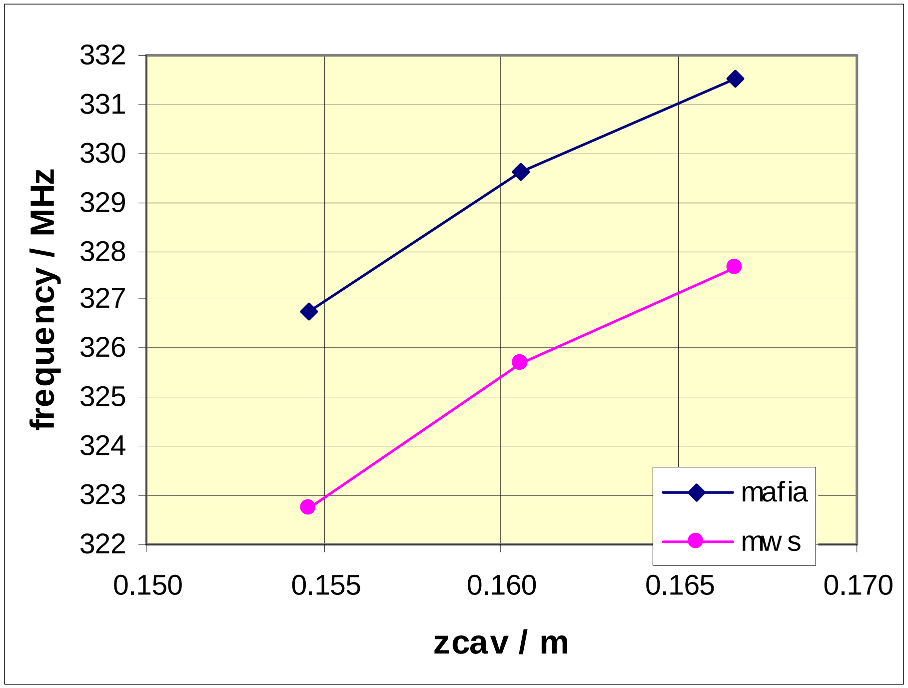
4-GAP SC H-CAVITY (320 MHz , β=0.2)



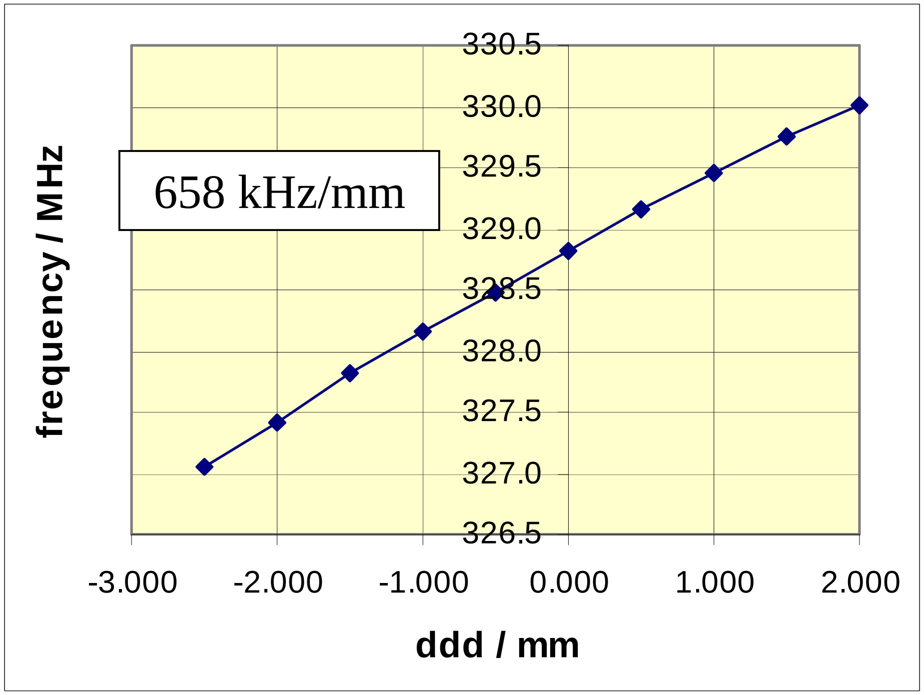
4-GAP SC H-CAVITY (320 MHz , β=0.2)

(tuning)

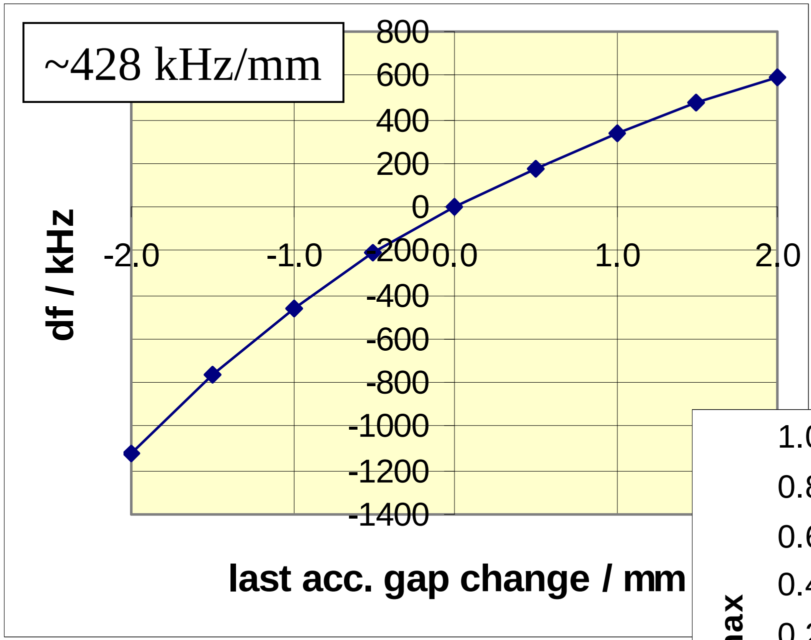
tuning by cavity length change

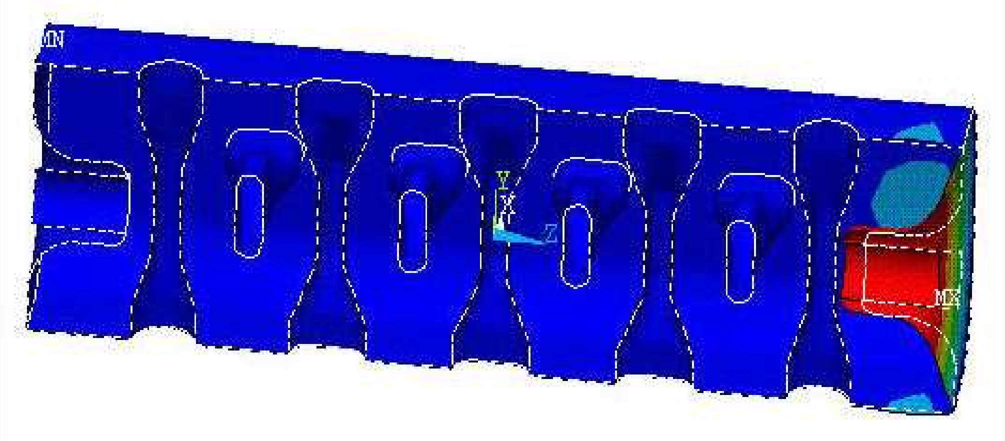


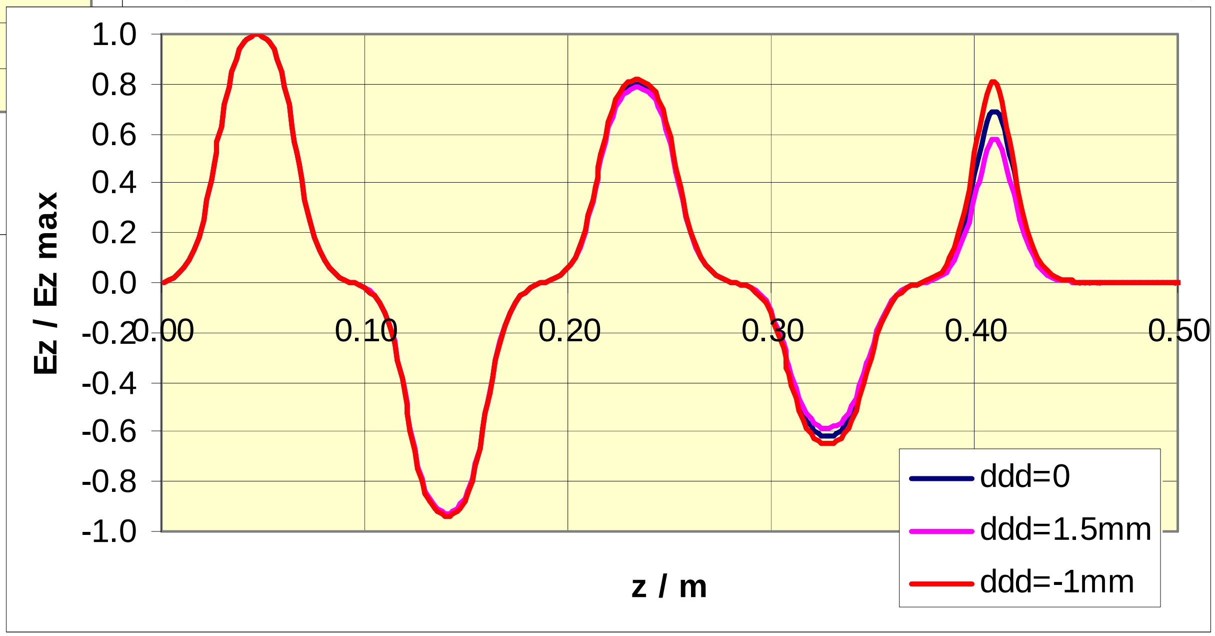
tuning by accelerating gap change



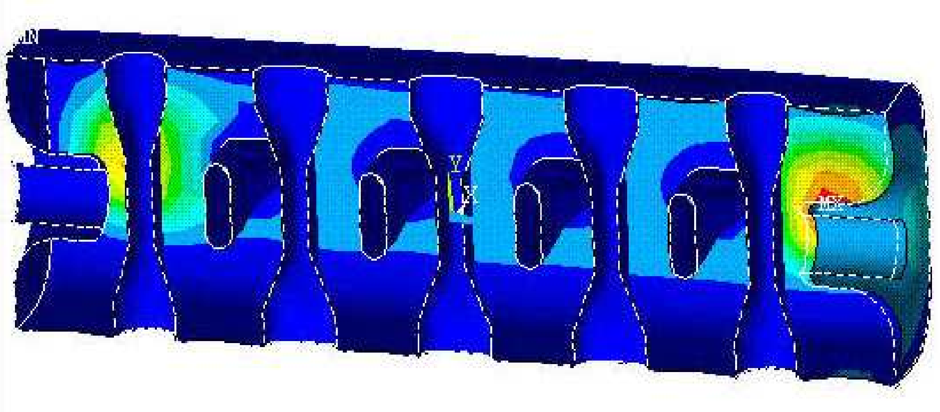
10-GAP SC H-CAVITY (320 MHz , β=0.2)
(tuning)

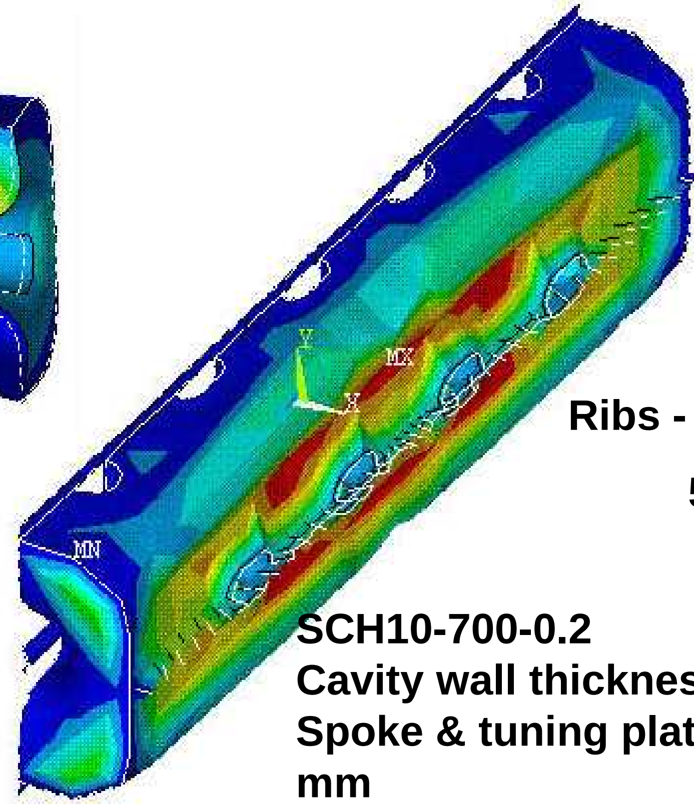






SCH-CAVITY UNDER 1 Bar PRESSURE





Ribs - 2 cm high

5 mm thick

SCH10-700-0.2
Cavity wall thickness – 2 mm
Spoke & tuning plate walls – 1 mm
Max deformation = 0.0185 mm
Max Stress von Mises = 9.9 MPa

SCH10-320-0.3
Cavity wall thickness – 3 mm
Spoke & tuning plate walls – 1 mm
Max deformation = 1.579 mm
Max Stress von Mises = 193 MPa

SCH10-700-0.2
Cavity wall thickness – 2 mm
Spoke & tuning plate walls – 1 mm
Max deformation = 0.00834 mm
Max Stress von Mises = 9.3 MPa

SCH10-320-0.3
Cavity wall thickness – 3 mm
Spoke & tuning plate walls – 1 mm

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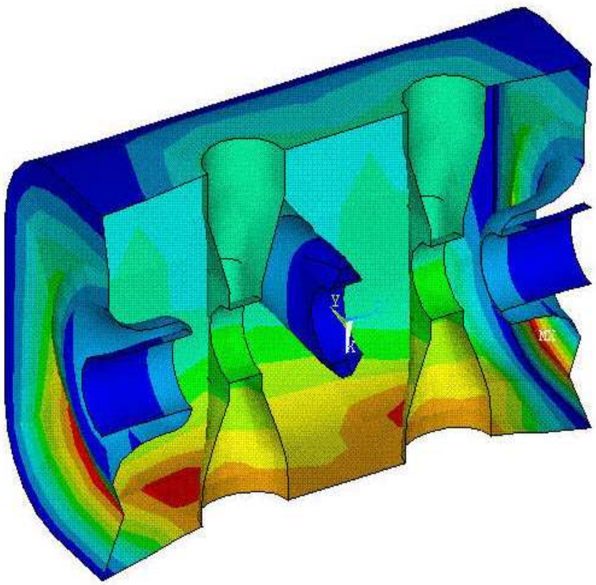
SCH-CAVITY UNDER 1 Bar PRESSURE & COOL-DOWN

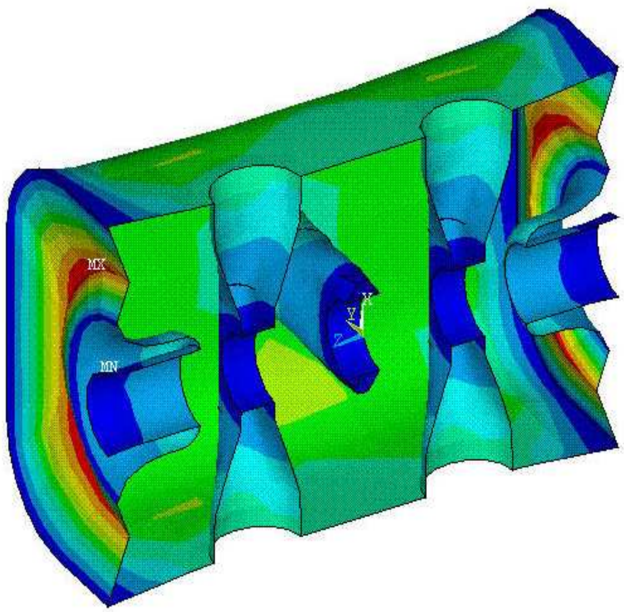
700 MHz, β=0.2

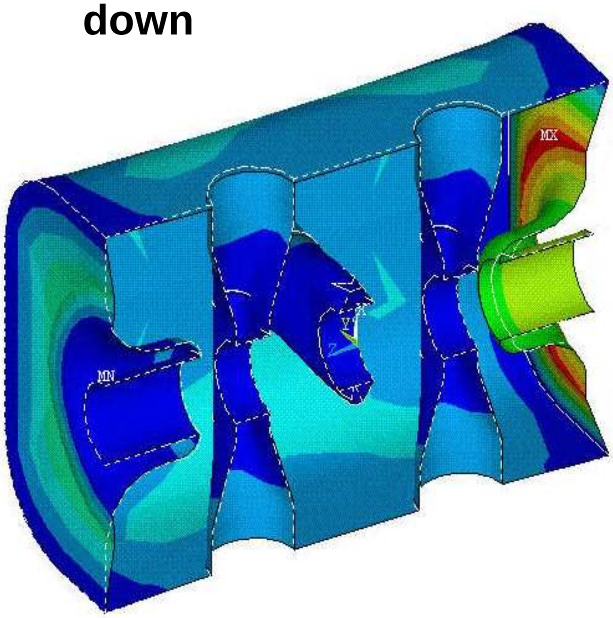
cool-down process

cool-down to 2K

1 bar + tuning + cool-down







max displacement 0.273 mm
max von Mises stress 431 Pa

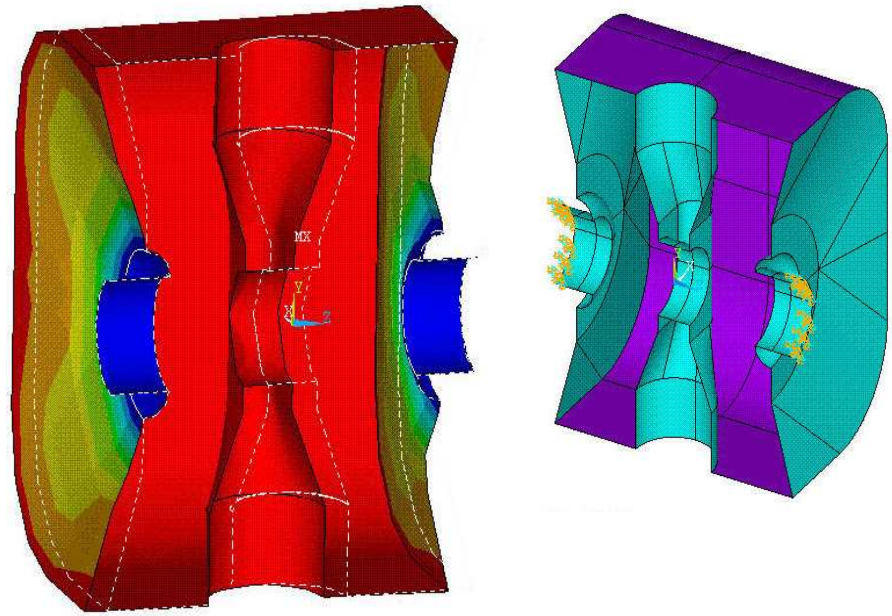
max displacement 0.413 mm,
max von Mises stress 633 Pa

end electrode shift +/-2 mm
max displacement 2/2.26 mm,
max von Mises stress 679/870 MPa
tuning pressure 55.33/16.37 kN

SPOKE-CAVITY DYNAMIC ANALYSIS

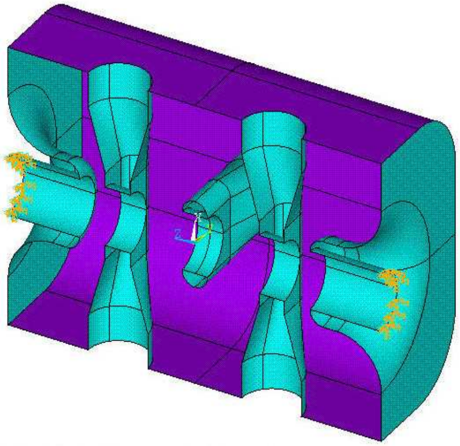
Table 3. Modal Analysis Results of Spoke Cavity

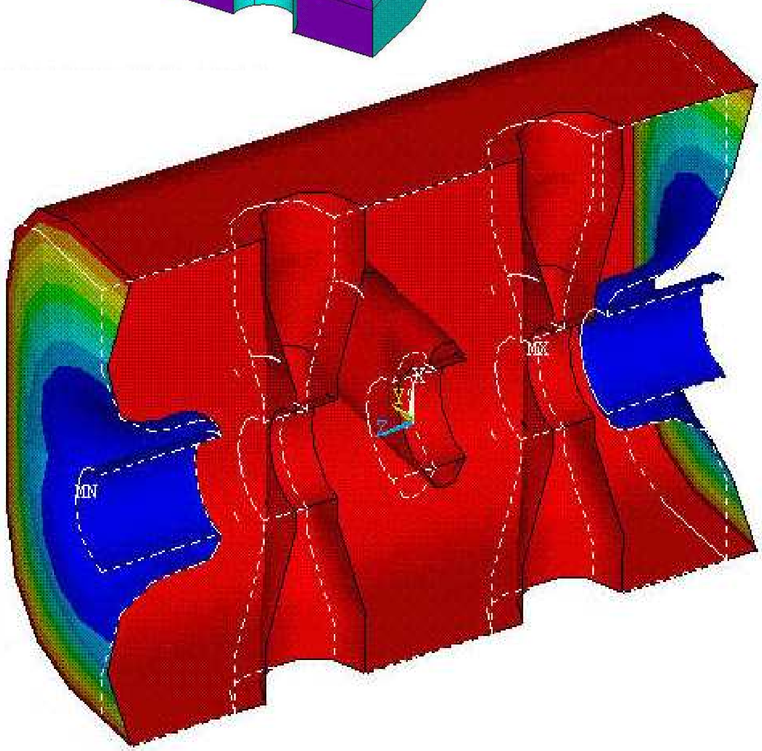
Spoke Cavity 700 - 0.2		**Spoke Cavity 320 – 0.3**	
Frequency / Hz	*frequency / Hz*	*frequency / Hz*	*frequency / Hz*
Full	half YZ	full	full
walls 2/1	walls 2/1	walls 2/1	walls 3/3
275.179	274.245	50.1	94.853
492.504		57.452	75.506
589.763	570.286	74.267	150.375
698.115	697.078	74.606	152.544
698.122		86.655	144.097
815.524		92.018	
877.013	876.885	162.638	
1053	1005	164.155	255.193
	1307		176.949
	1507		266.892
	1609		



Mode 1 is an elementary swinging (first eigen frequency) along the longitudinal ax of the cavity.
Mode 2 is a torsion oscillation.
Mode 3 is a tilted oscillation relative to the cavity ax.
Mode 4 is an oscillation of the cavity walls without spokes.
Modes 5 & 6 are similar to mode 3 with different directions of oscillations.
Mode 7 is the same as mode 4 of wall oscillations but with p phase shift.
Mode 8 is an oscillation of end plate walls.

SC 4-GAP CAVITY DYNAMIC ANALYSIS





sch4g 700-0.2					
Freq / Hz	*Freq / Hz*	*Freq / Hz*	*Freq / Hz*	*Freq / Hz*	*Freq / Hz*
full		half YZ		half XZ	
walls 2/1	walls 3/3	walls 2/1	walls 3/3	walls 2/1	walls 3/3
125.435	327.659	123.518	321.375	123.848	323.281
235.935	434.449			233.693	426.4
238.875	449.598	235.475	432.86		
251.018	333.436				
283.487	550.072			282.279	542.559
285.227	568.97	285.838	564.032		
543.119	732.491	490.546	703.532		
569.819	831.133			547.355	814.254
		844.565	1195	658.441	877.497
		867.63	1365	857.749	1158
		884.88	1175	935.021	1242
		938.662	1441	1002	1389

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SC 10-GAP CAVITY DYNAMIC ANALYSIS

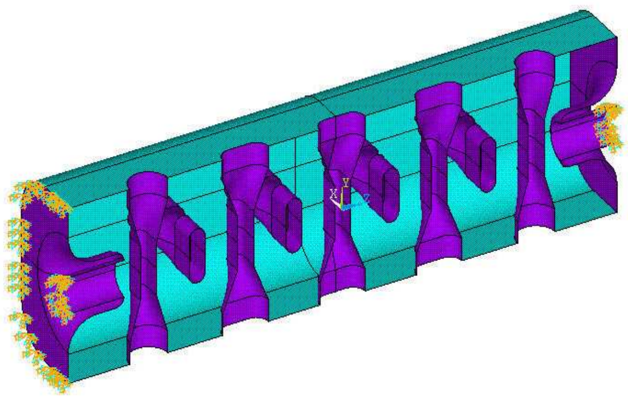
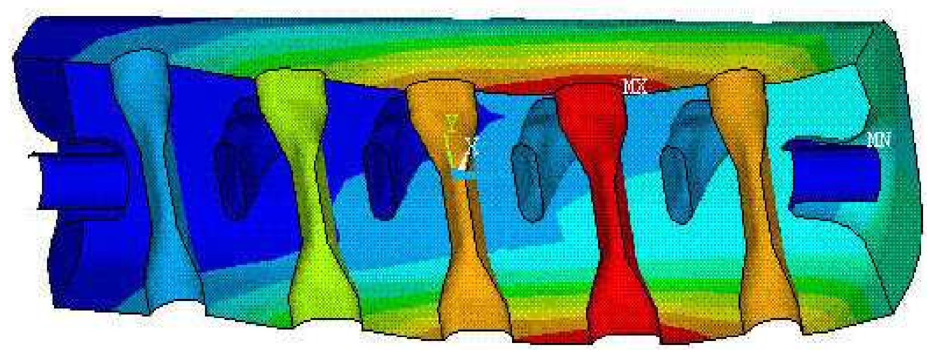


Table 6. Modal Analysis Results of SC 320 MHz, β=0.3 10-gap H-Cavity

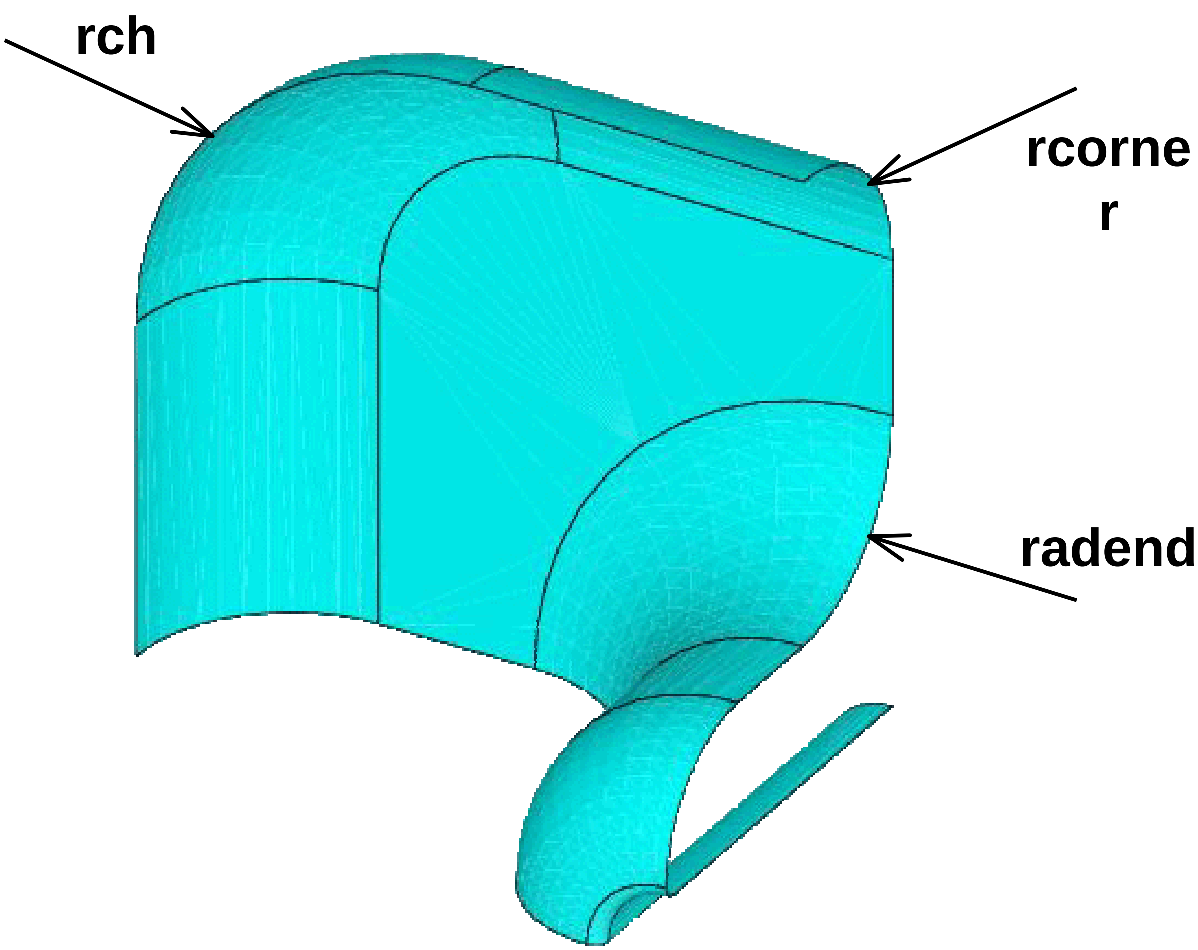
sch10g 320–03 both ends fixed				
frequency / Hz	*frequency / Hz*	*frequency / Hz*	*frequency / Hz*	*frequency / Hz*
half YZ	half YZ	half YZ	half YZ	half YZ
walls 2/1	walls 3/1	walls 3/3	walls 3/1 + ribs	walls 3/1 + 2ribs
63.141	86.512	82.499	113.552	94.078
84.428	114.539	105.034	196.821	153.138
103.745	145.107	129.279	287.855	225.853
117.236	165.344	148.337	306.677	275.263
118.234	167.795	149.269	306.677	286.433
184.267	240.284	267.676	316.893	303.925
186.075	256.78	268.447	322.188	339.284
199.696	263.74	306.674	351.981	349.741

Sch10g 700-0.2		**sch10g 320-03**			
Freq / Hz	*Freq / Hz*	*Freq / Hz*	*Freq / Hz*	*Freq / Hz*	*Freq / Hz*
half YZ	half XZ	half YZ		half XZ	
walls 2/1	walls 2/1	walls 2/1	walls 3/3	walls 2/1	walls 3/3
284.287				57.009	71.639
	284.418	57.216	71.825		
	387.09			75.987	93.3
392.318		78.718	95.532		
	469.385			93.002	113.722
477.744		95.572	114.115		
	542.391			104.955	124.138
562.876		106.058	131.076		
624.596				110.145	134.229
	640.763	117.734	148.742		
667.11		124.691	155.22		
	795.167			138.156	218.446
	911.822			153.267	232.248
	921.408			159.683	238.188
924.334		162.453	245.489		
997.703		184.448	268.03		



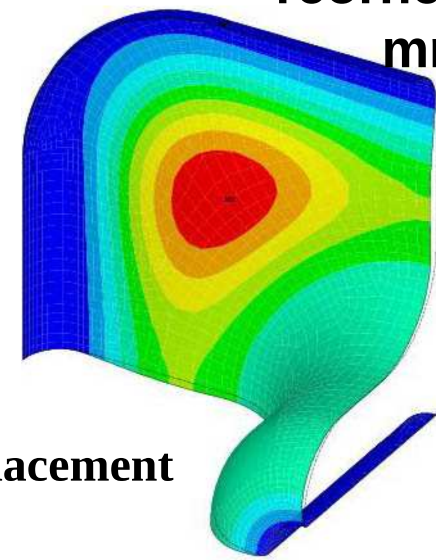
mode 1

TUNING PLATE GEOMETRY OPTIMISATION
(320 MHz , β=0.2)

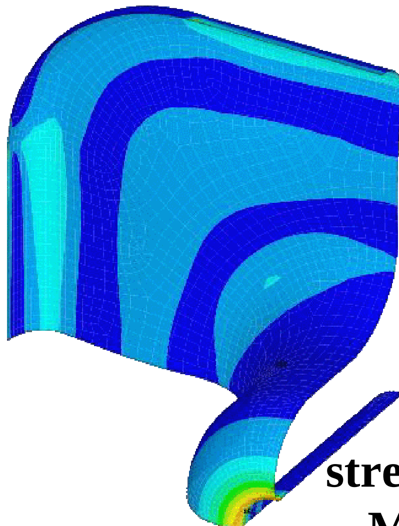


TUNING PLATE UNDER 1 Bar LHe PRESSURE (rcorner)

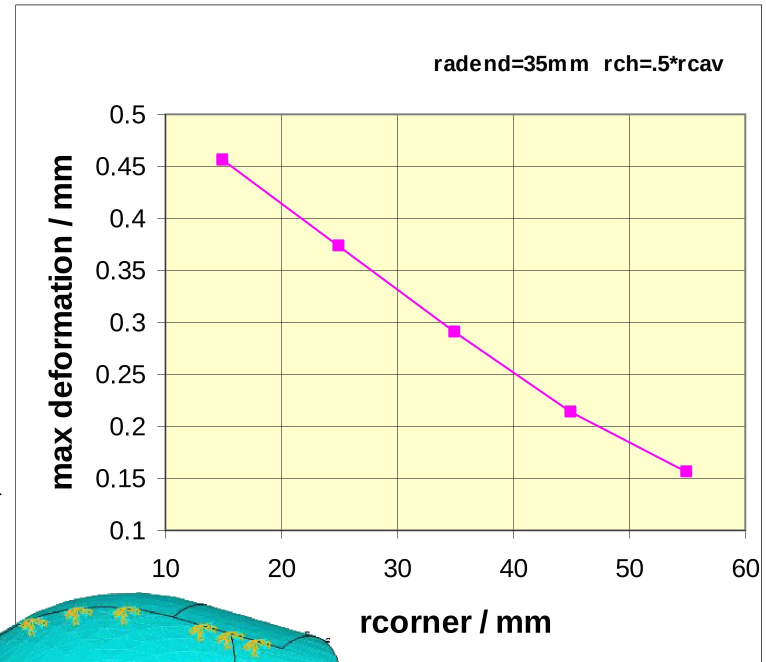
rcorner = 15 mm

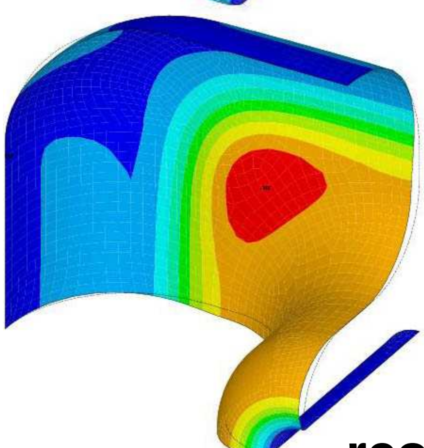


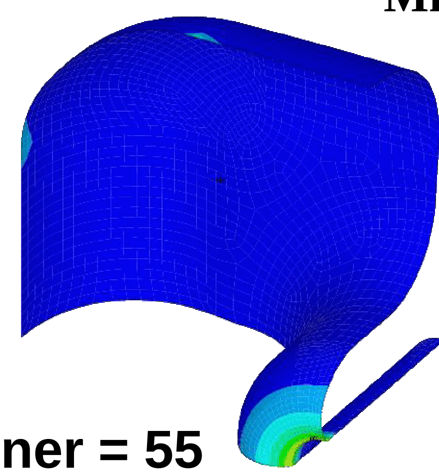
displacement

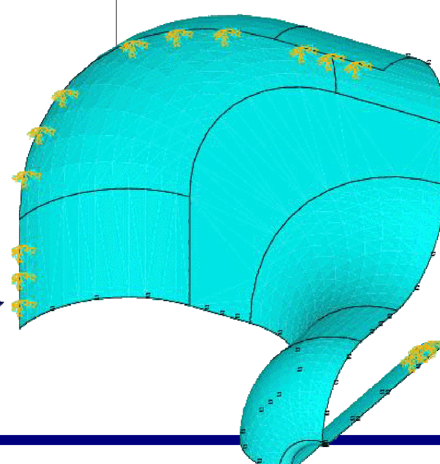


stress von Mises



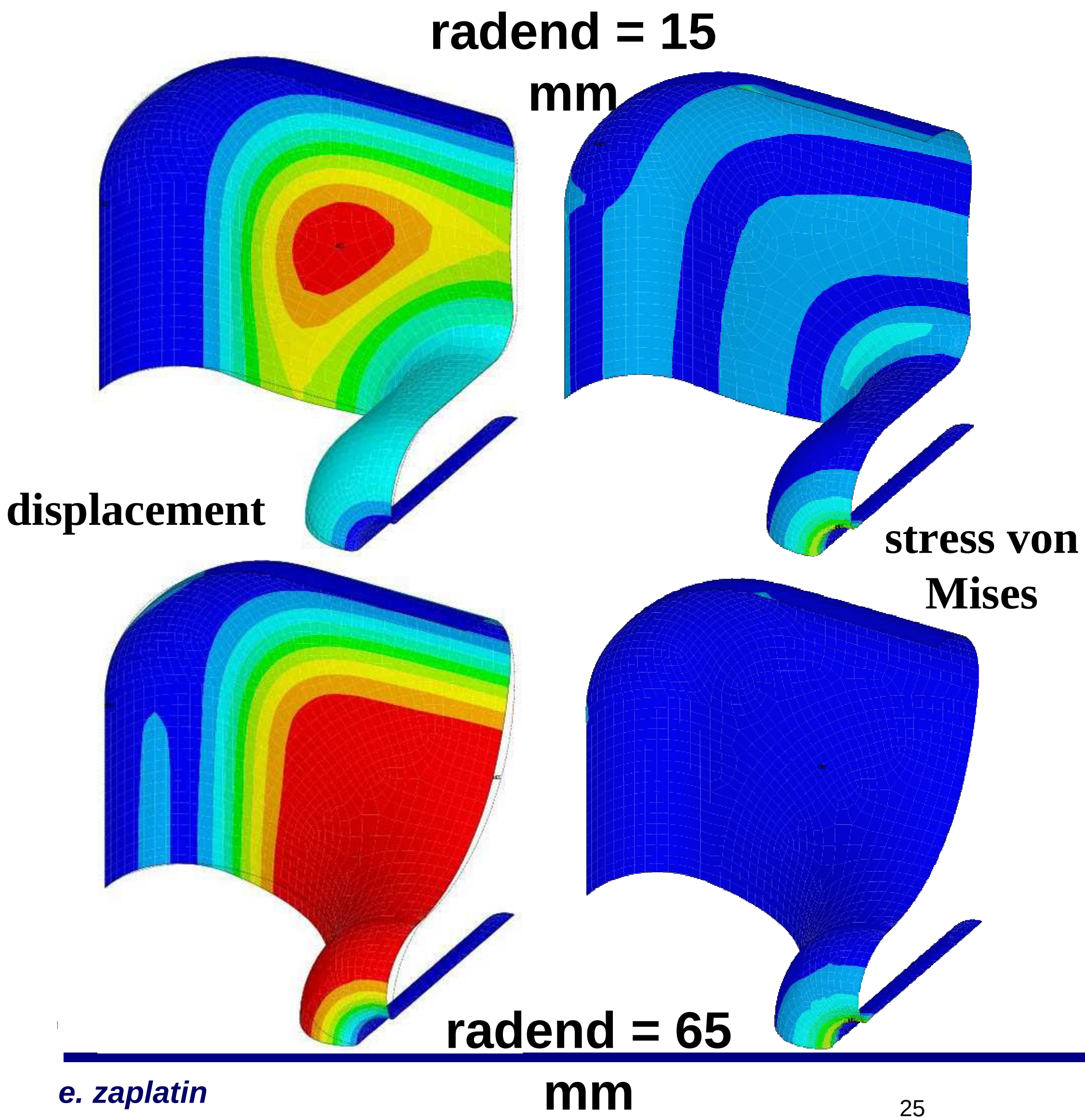


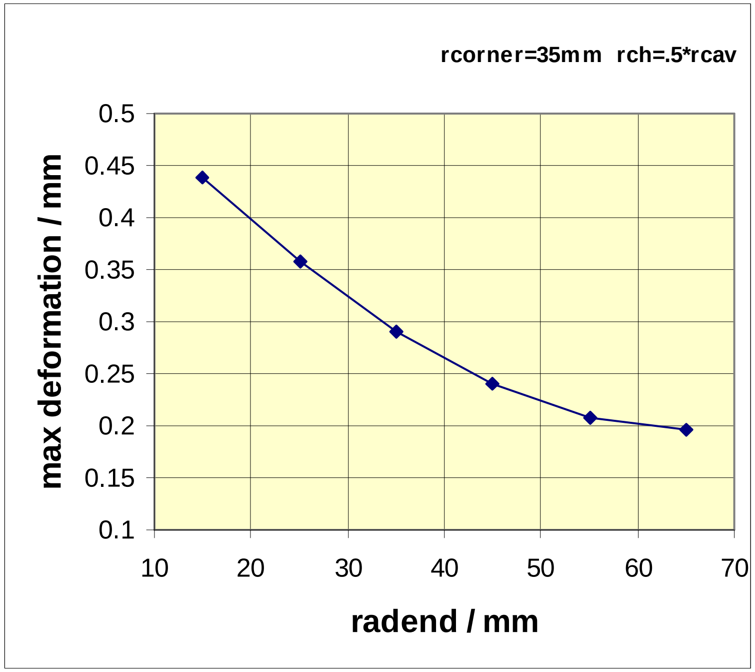




rcorner = 55 mm

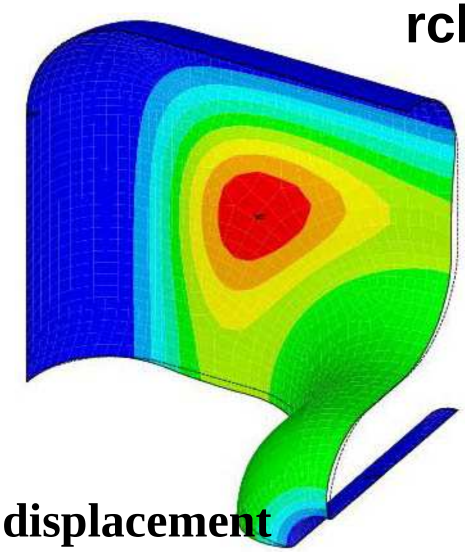
TUNING PLATE UNDER 1 Bar LHe PRESSURE (radend)

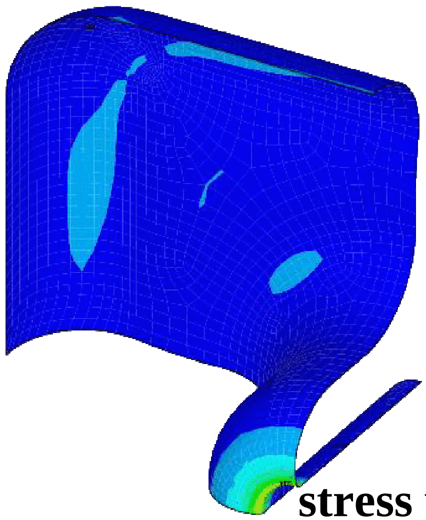




TUNING PLATE UNDER 1 Bar LHe PRESSURE (rch)

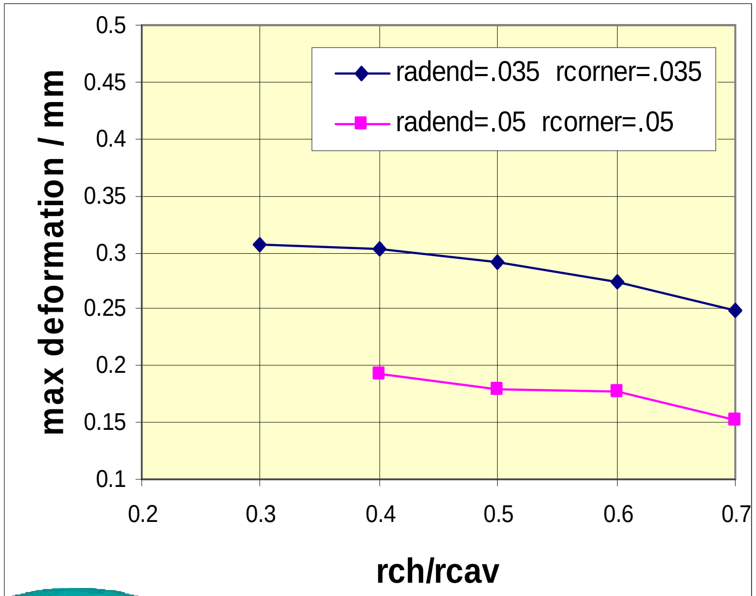
rch / rcav = 0.3

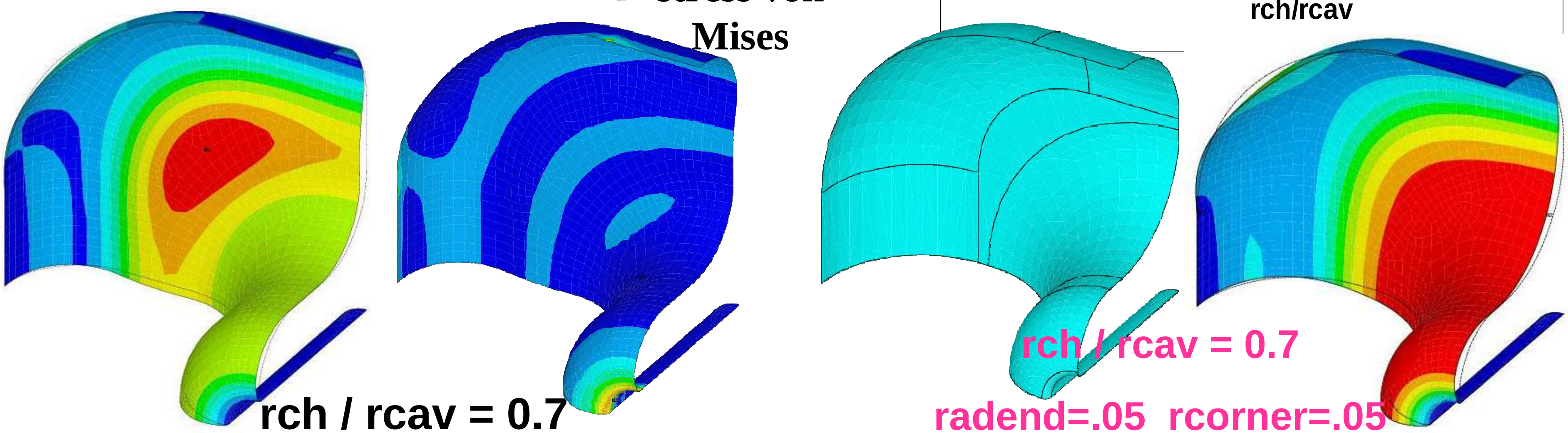




displacement

stress von Mises





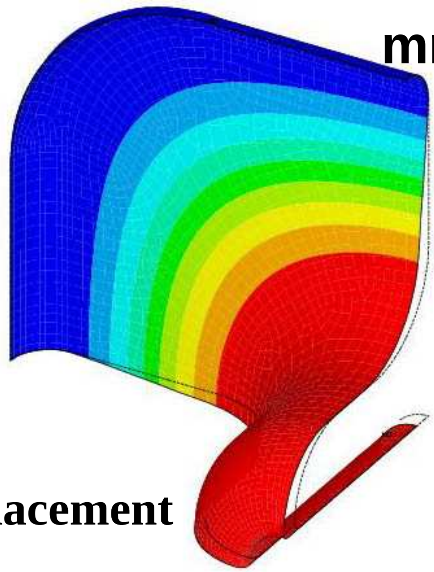
rch / rcav = 0.7

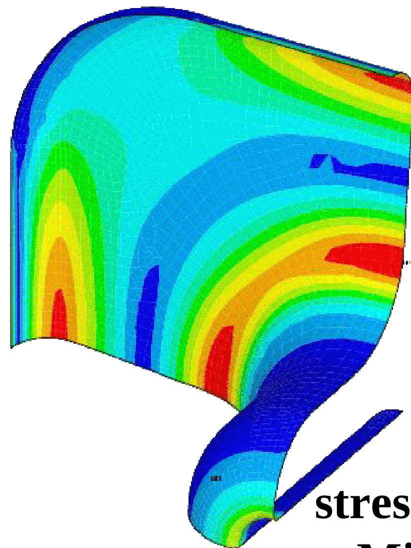
rch / rcav = 0.7

radend=.05 rcorner=.05

TUNING PLATE UNDER TUNING FORCE (rcorner)

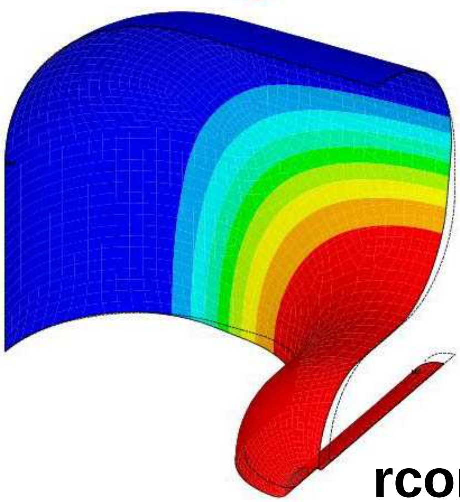
rcorner = 15 mm

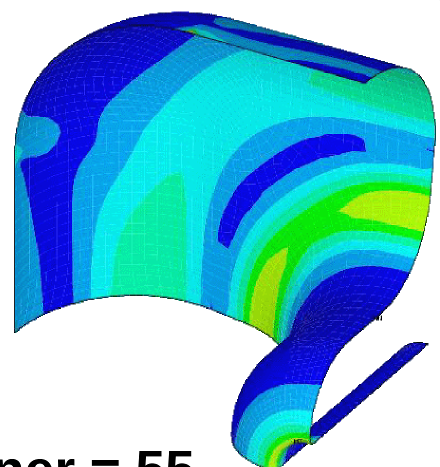




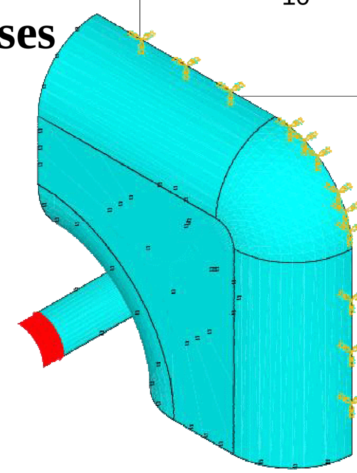
displacement

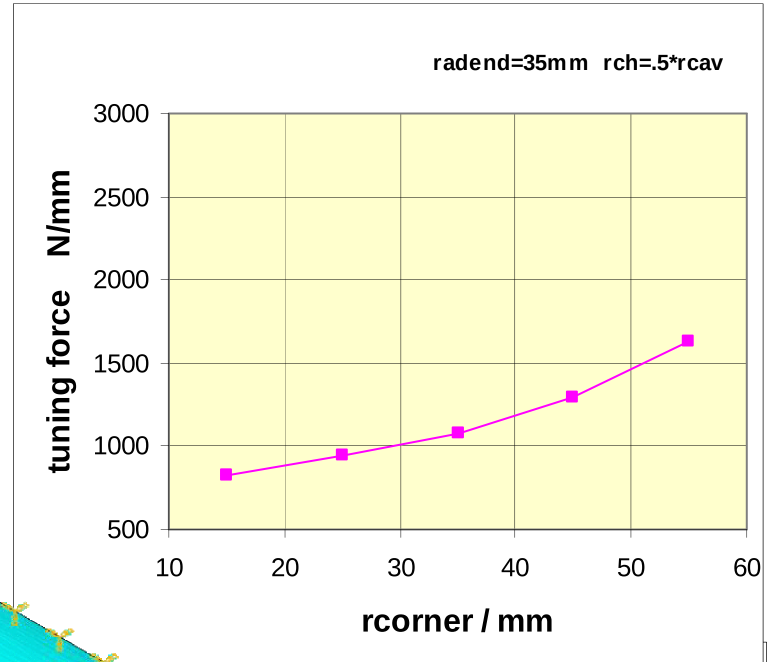
stress von Mises

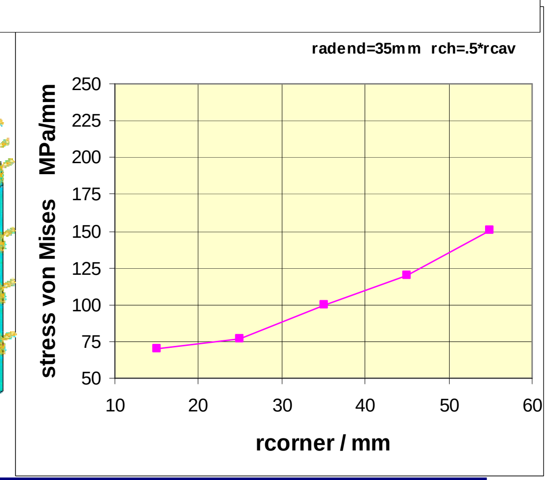




rcorner = 55 mm

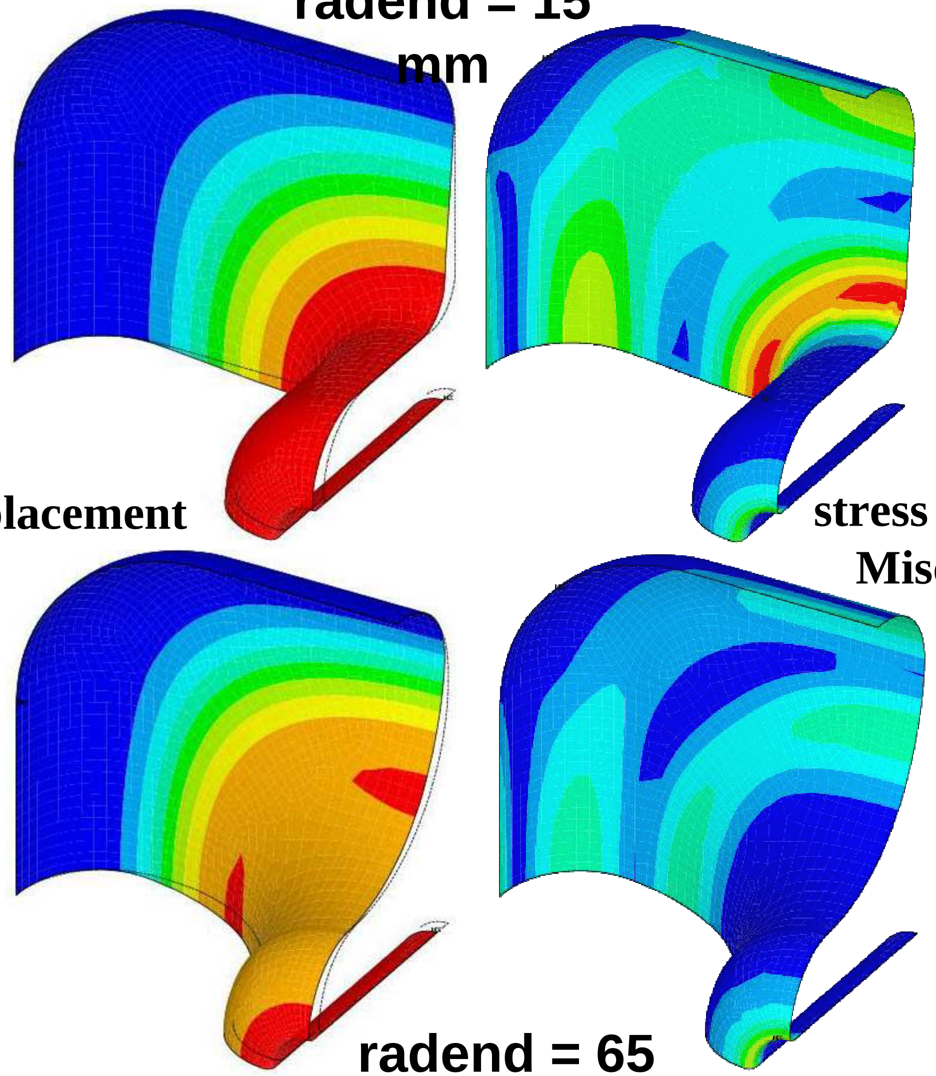






TUNING PLATE UNDER TUNING FORCE
(radend)

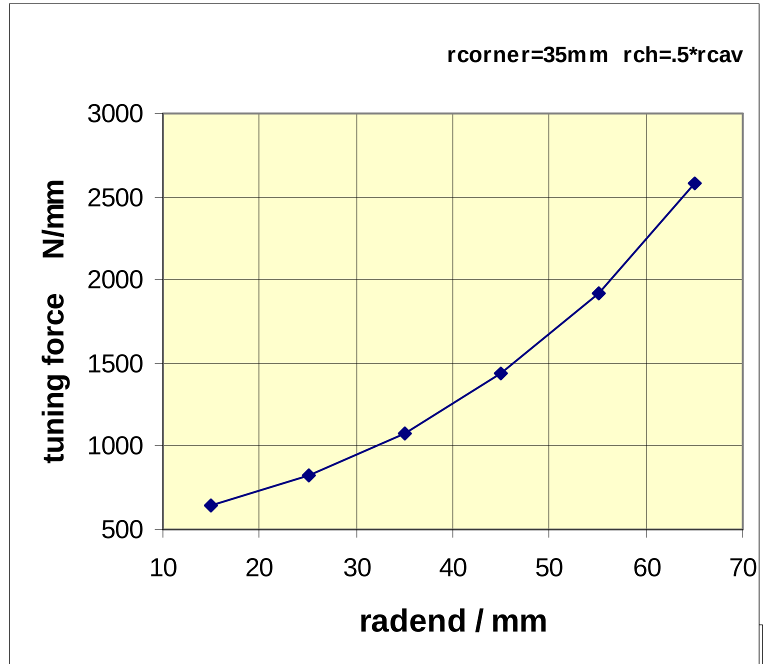
radend = 15 mm

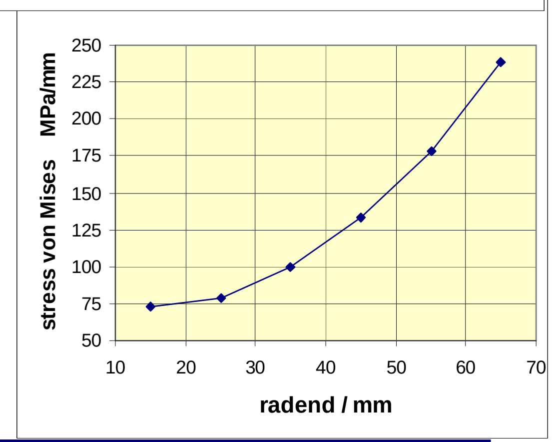


displacement

stress von Mises

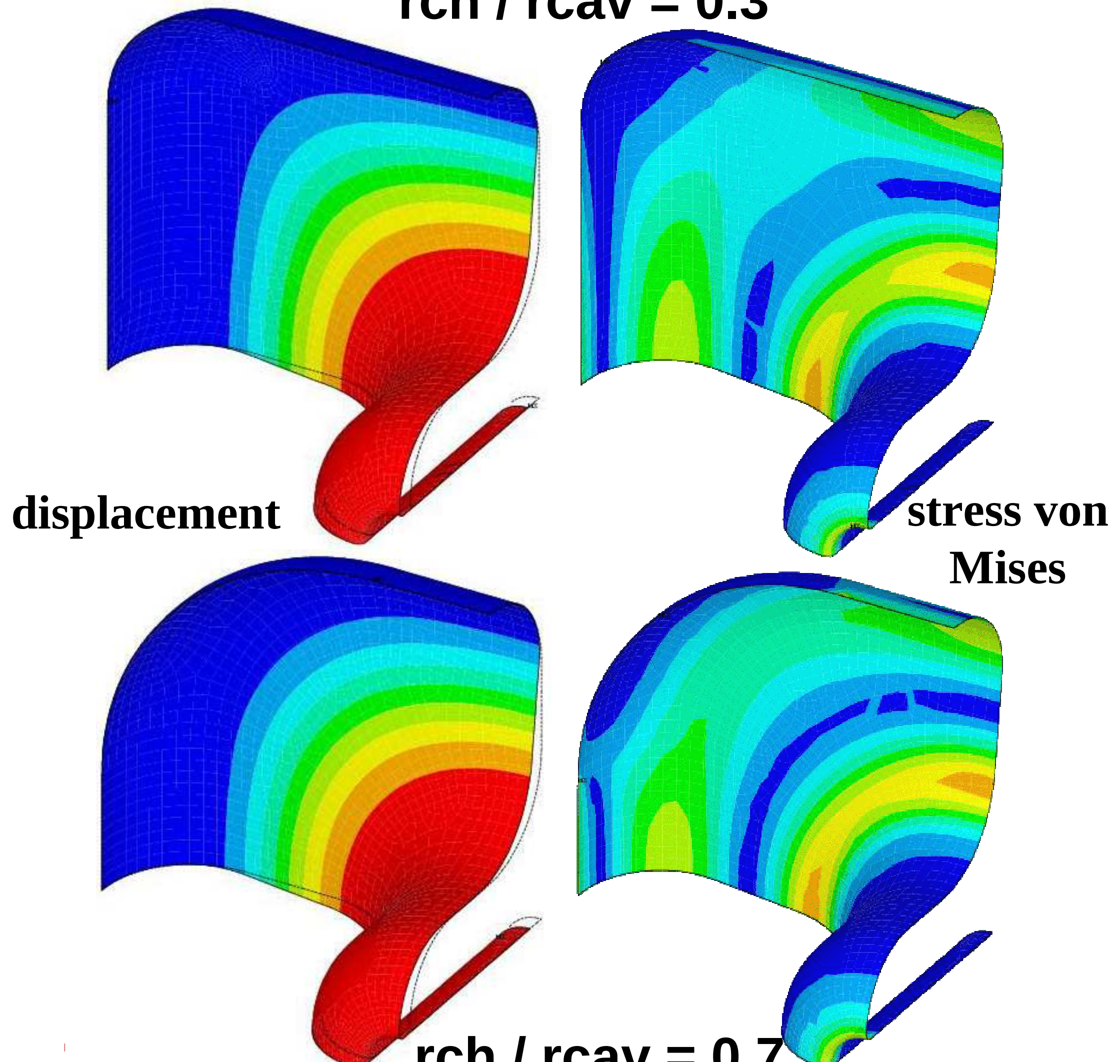
radend = 65 mm



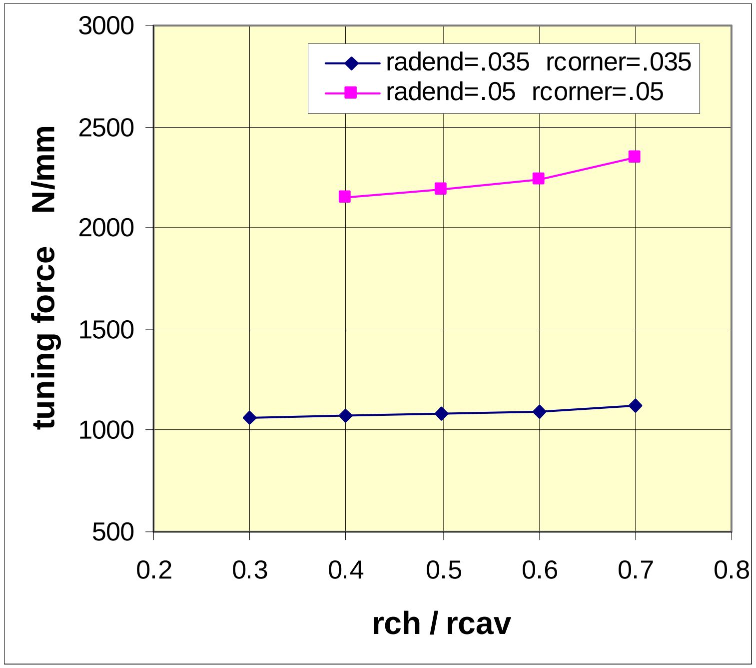


TUNING PLATE UNDER TUNING FORCE (rch)

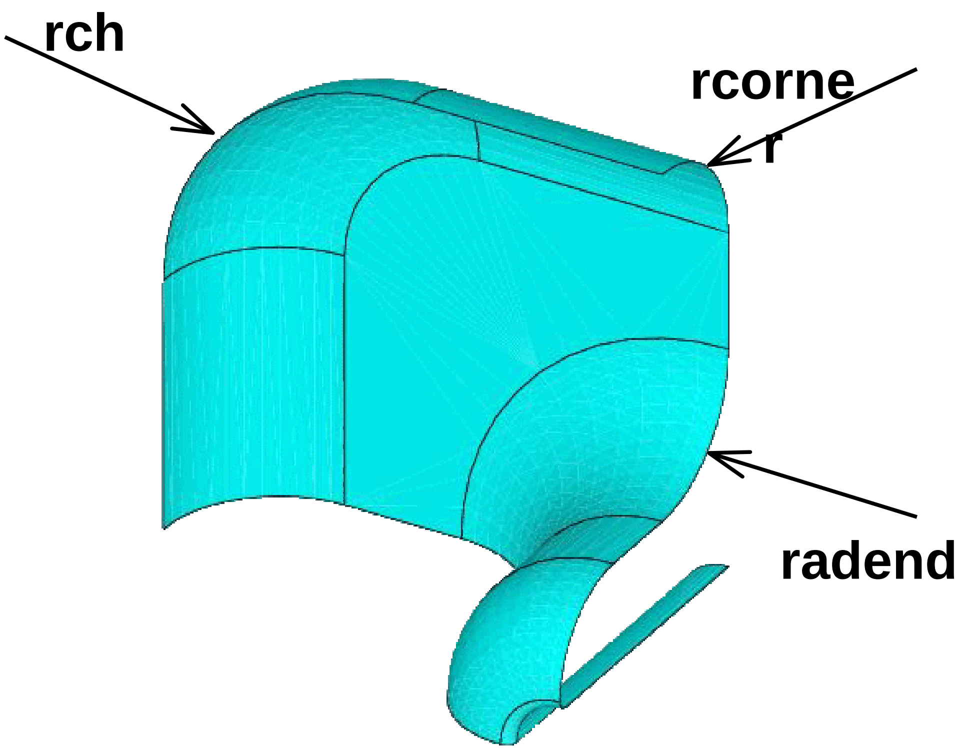
rch / rcav = 0.3

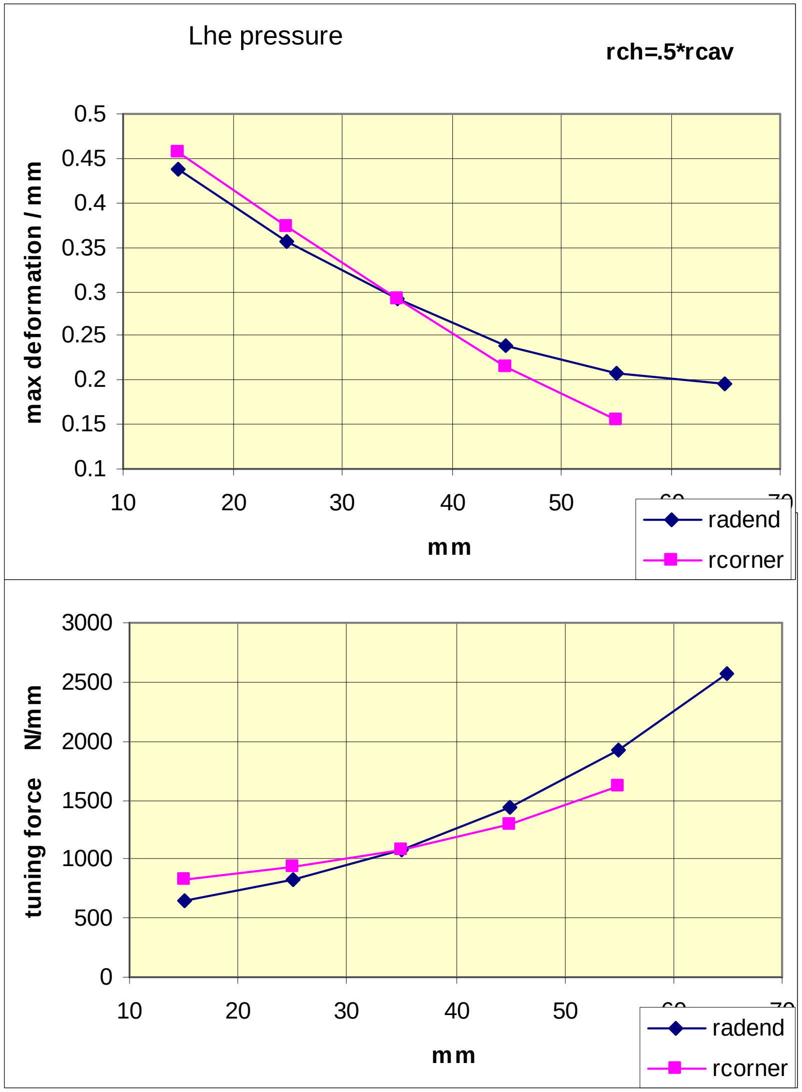


rch / rcav = 0.7

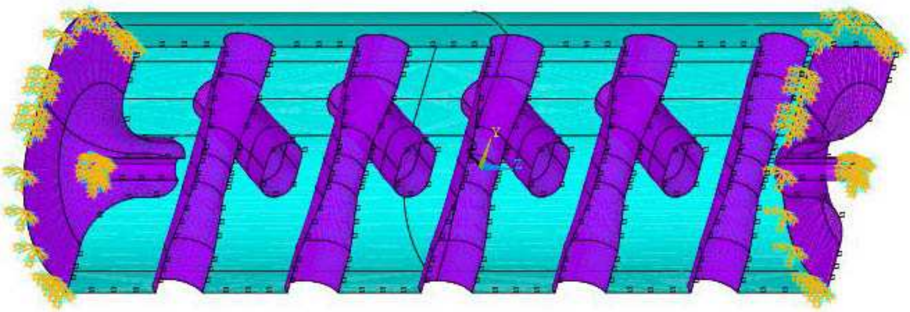


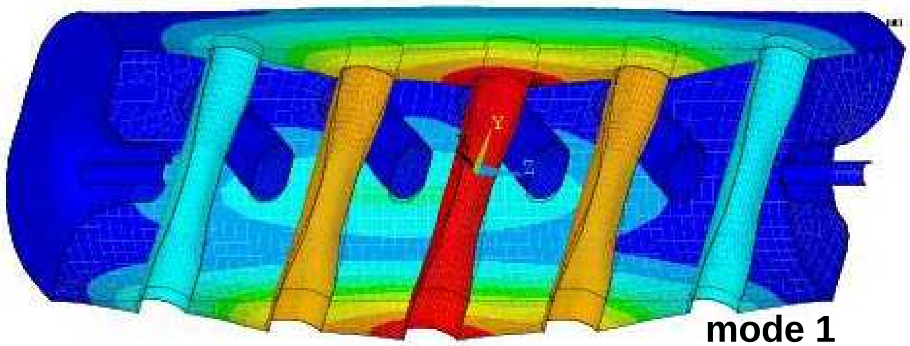
TUNING PLATE GEOMETRY OPTIMISATION
(320 MHz , β=0.2)

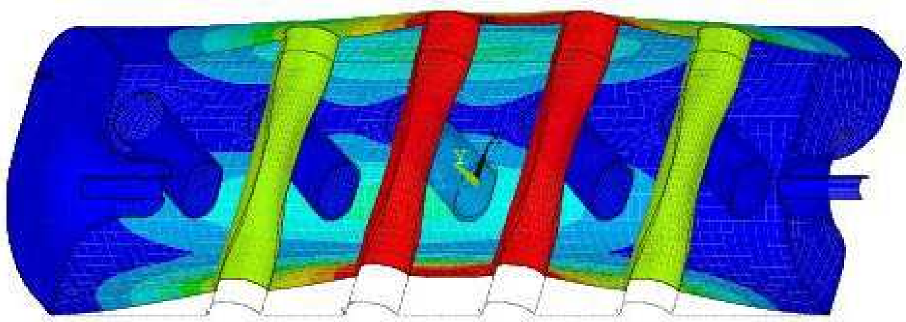




SCH10G MODAL ANALYSIS
(320 MHz , β=0.2)

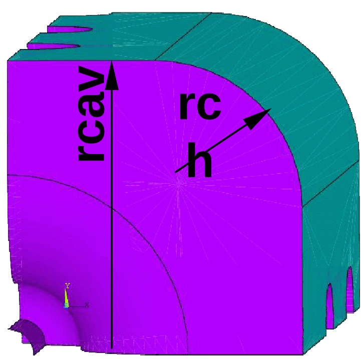


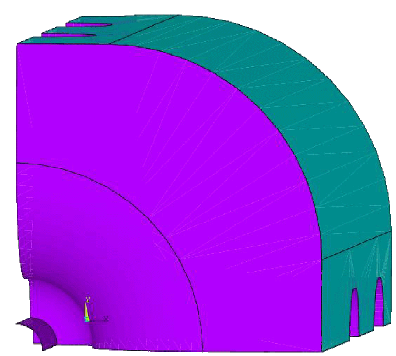

mode 1


mode 2

mode	rch=0.5*rcav	rch=0.7*rcav
	Hz	Hz
1	130.045	175.789
2	131.699	176.504
3	174.513	247.326
4	178.395	250.752
5	216.88	304.761
6	217.045	305.744
7	242.665	338.451
8	250.708	343.285

*) walls 4 / 2





Discussion on "Electrodynamics & Mechanics of Multigap Low-beta SC Structures" by Evgeny Zaplatin

Zaplatin was asked about the trade-off between cylindrical cavity cross-section and the square cross-section that he is proposing. He showed that the peak magnetic field is reduced by 10 % by introduction of the square corss-section. He also pointed out that this design allows for purely 2D weldings, which gives more options on the machine shops that could do the fabrication. His optimum design still has a large corner radius. This has been the result of a mechanical stability study. Their final endwall shape does only require minimal additional stiffening.

He also was asked if tuning a spoke resonator by the endwall is the best way to do tuning. Or if one could for example envision to add a tuning feature in the spoke itself and make the endwall rigid. Zaplatin in response did address the large tuning range of his endwall design (in the 700 MHz case). This shows that tuning this way is efficient.

The LANL Advanced Accelerator Applications (AAA) Program

Dale Schrage, LANL

The Advanced Accelerator Applications (AAA) Program is a United States Department of Energy (DOE) National Program Addressing National Priorities and Needs. It was authorized by Congress to begin in fiscal year 2001. The AAA program was created to address pressing nuclear issues facing the United States:

- nuclear energy and waste management concerns
- declining US nuclear infrastructure
- global nuclear leadership

The main focus of the AAA Program accelerator technology work has been in the area of spoke resonators. The present status and preliminary six-year plan for the accelerator technology work will be presented.

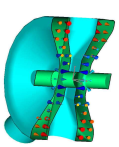
LA-UR-02-6141

The LANL ADVANCED ACCELERATOR APPLICATIONS PROJECT

Dale Schrage
LANL

Workshop on the Advanced Design of Spoke Resonators

Los Alamos, NM, USA
October 7 and 8, 2002



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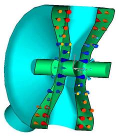
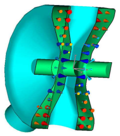
AAA PROGRAM

- **Authorized by Congress to begin in fiscal year 2001, the DOE Advanced Accelerator Applications (AAA) program was created to address pressing nuclear issues facing the United States:**
  - nuclear energy and waste management concerns
  - declining US nuclear infrastructure
  - global nuclear leadership
- **website: http://aaa.lanl.gov/**



AAA PROGRAM

- DIRECTION & FUNDING PRESENTLY UNCLEAR
- ADVANCED ACCELERATOR APPLICATIONS PROGRAM MAY BECOME "ADVANCED FUEL CYCLES PROGRAM"
- OR, THERE MAY BE TWO SEPARATE PROGRAMS
- DECISION WILL BE LATER IN FY2003
- PROPOSAL IN US CONGRESS FOR ACCELERATOR DRIVE TEST FACILITY



LA-UR-02-6141

ACCELERATOR TRANSMUTATION OF WASTE

WHY SPOKE CAVITIES?

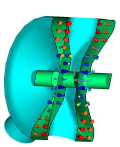
- TECHNICAL SUPERIORITY TO DTL & CCDTL
- INDUSTRIAL FABRICATION PROVEN
- COMPARABLE INSTALLED COST
- LOWER OPERATING COST
- HIGHER RELIABILITY

AAA PROGRAM FY2003 PRELIMNARY PLAN

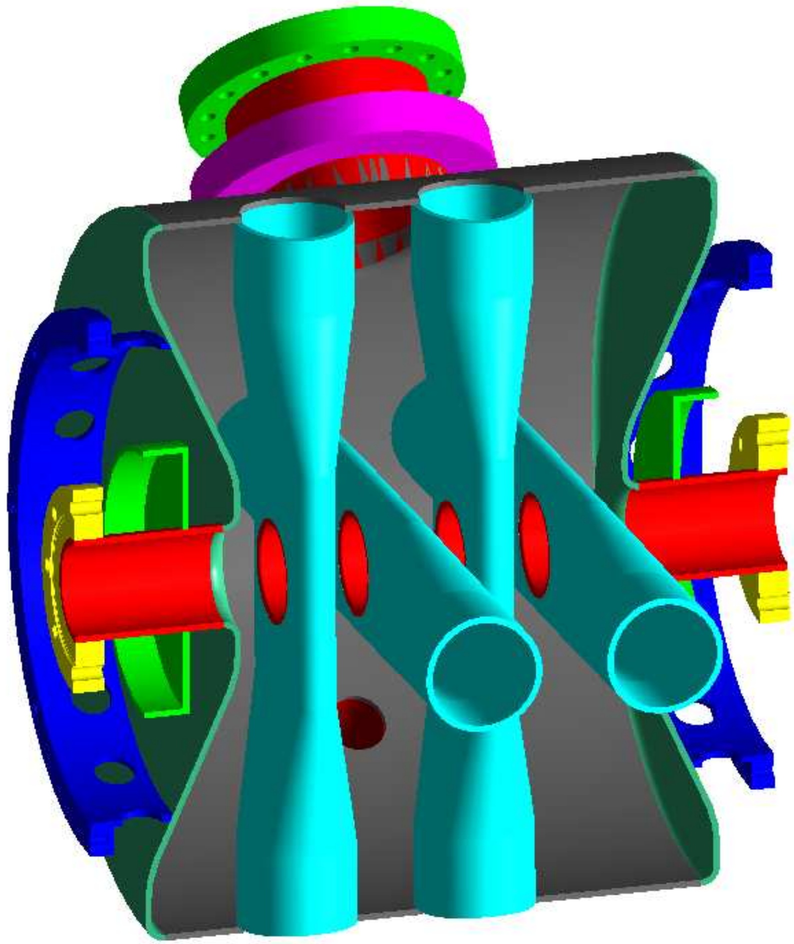
- **CEA/CNRS/DOE COLLABORATION**
- **DESIGN/BID POWER COUPLER**
- **DESIGN/SPECIFY ELECTROPOLISHING FACILITY**
- **ATW STUDY**
- **NIOBIUM STUDY w/JLAB & UVA**
- **INFORMAL COLLABORATION WITH ANL**
- **INFORMAL COLLABORATION WITH INFN**

CEA/CNRS/DOE COLLABORATION

- **ELLIPTICAL CAVITIES:**
  - DESIGN/PROCURE/TEST β = 0.5, 5-CELL, 704.4 MHz CAVITIES (2ea)
- **SPOKE CAVITIES:**
  - CONTINUE TESTS OF EXISTING CAVITIES:
    - LANL: β = 0.175, 2-GAP, 350 MHz CAVITIES (2ea)
    - CNRS: β = 0.34, 2-GAP, 352.2 MHz CAVITY
  - DESIGN/ β = 0.125, 5-CELL, 350 MHz CAVITIES (2ea)
  - PROCURE/TEST β = 0.125, 5-CELL, 350 MHz CAVITIES (2ea) in FY2004 & FY2005



β = 0.125, 5-GAP, 350 MHz CAVITY

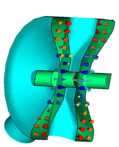


DESIGN/BID POWER COUPLER

- **FABRICATE IN INDUSTRY**
- **BID IN June 2003, AWARD IN October 2004**
- **OPTIMIZED FOR ATW REQUIREMENTS**
- **PRELIMINARY REQUIREMENTS**
  - **20 mAmps**
  - **β = 0.175 (2-Gaps) - β = 0.34 (3-Gaps)**
  - **E_{acc} = TBD (~ 8 Mvolt/meter)**
  - **Power ~ 30 Kwatts**

DESIGN/SPECIFY ELECTROPOLISHING FACILITY

- OBJECTIVE IS TO IMPROVE PERFORMANCE OF ELLIPTICAL CAVITIES
- DESIGN & SPECIFY IN FY2003
- PROCURE & INSTALL IN FY2004
- OPERATE IN FY2005

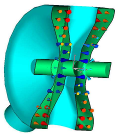


ATW STUDY

- **PERFORM LIMITED SCOPE TRADE STUDY TO CONSIDER SPOKE CAVITIES @ $\beta \sim 0.6$**
  - **Collaboration with RIA Project**

NIOBIUM STUDY w/JLAB & UVA

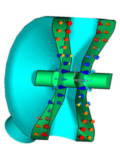
- 3-YEAR PROGRAM IN COLLABORATION WITH JLAB & UVA TO IMPROVE THE PROPERTIES OF NIOBIUM
- EMPHASIS ON IMPROVING THE MANUFACTURING PROCESSES TO IMPROVE BATCH-TO-BATCH CONSISTENCY



LA-UR-02-6141

6-YEAR PLAN

TASK	FY2003	FY2004	FY2005	FY2006	FY2007	FY2008
Lab Operations	• Level of Effort	• Level of Effort	• Level of Effort	• Level of Effort	• Level of Effort	• Level of Effort
DOE/CEA/CNRS Collaboration	• Final Lab Tests of β=.175 Spoke Cavity • Des/Bid β=.125 Spoke Cavity • Des/Bid Power Coupler for β=.125 Spoke Cavity • Des/Bid β=.47 Elliptical Cavity	• Procure β=.125 Spoke Cavities • Procure Power Coupler for β=.125 Spoke Cavities • Procure β=.47 Elliptical Cavities • Design β=.60 Elliptical Cavity	• Lab Test of β=.125 Spoke Cavities • Lab Test of Power Coupler for β=.125 Spoke Cavities • Lab Test of β=.47 Elliptical Cavities • Procure β=.60 Elliptical Cavities • Concept of Cryostat for β=.175 Spoke Cavities	• Lab Test of β=.60 Elliptical Cavities • Concept of Cryostat for β=.125 Spoke Cavities • Concept of Cryostat for β=.47 Elliptical Cavities	• Concept of Cryostat for β=.60 Elliptical Cavities • Des/Proc Cold Test of Power Coupler for β=.125 Spoke Cavities	• Cold Test of Power Coupler for β=.125 Spoke Cavities
Power Couplers	• Des/Bid Power Coupler for β=.175 Spoke Cavity	• Procure Power Coupler for β=.175 Spoke Cavities	• Lab Test of Power Coupler for β=.175 Spoke Cavities	• Des/Bid Power Coupler for β=.60 Elliptical Cavities	• Des/Proc Cold Test of Power Coupler for β=.175 Spoke Cavities • Proc Power Coupler for β=.60 Elliptical Cavities	• Cold Test of Power Coupler for β=.175 Spoke Cavities • Lab Test of Power Coupler for β=.60 Elliptical Cavities
Lab Improvements	• Study Epolish System	• Proc/Install Epolish System	• Test Epolish System with APT Cavities • Des/Specify Heat Treat System	• Proc/Install Heat Treat System	• Test Heat Treat System with APT Cavities	•
ADS Optimization	• Study β=.60 Spoke Cavity	• Des RF-focussed Spoke Cavity	• Beam Dynamics of ADS Linac • Proc RF-focussed Spoke Cavity	• ADS System Concept • Lab Test of RF-focussed Spoke Cavity • Lab Test of High Gradient Spoke Cavities	• ADS System Concept • Lab Test of High Gradient Spoke Cavities • Lab Test of High-Gradient Elliptical Cavties	• ADS System Concept • Lab Test of High Gradient Spoke Cavities • Lab Test of High-Gradient Elliptical Cavties



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Discussion on "The LANL Advanced Accelerator Applications (AAA) Program" by Dale Schrage

For future work at LANL the idea of using a 5-gap spoke resonator at β=0.125 was presented. Again the question on the related beam-dynamics simulations was raised. Schrage explained that the original β=0.175 2-gap structure was needed due to the 100 mA beam requirement. Now that this was dropped the 13-20 mA beam does allow lower β. Preliminary beam-dynamics has been done that shows the feasibility of the β=0.125, 5-gap structure. This solution has a much better real estate gradient than the original high current design.
Delayen pointed out that ANL at some point had a design for a high intensity linac that would have used β=0.125 spoke resonators. The high current there had even required using superconducting focusing elements very close to the cavities to maintain the longitudinal beam quality.
While a lot of designs require short spoke resonators after the RFQ, even for low beam current, LANL's advantage is that the RFQ is already providing a beam at 7 MeV, which allows longer focusing periods. The LANL RFQ on the other hand is optimized for 100 mA and cheaper, more optimized solutions could be envisioned if the front-end would have been designed for the lower beam currents needed for ADS systems.

Status of the High Current Proton Accelerator for the TRASCO Program

P. Pierini, INFN Milano

TRASCO (acronym for TRAsmutazione di SCOrie) is a joint INFN/ENEA program, started in 1998, aiming at the design and the technological investigation of the main components of an accelerator driven system (ADS) for nuclear waste transmutation. The proposed 30 mA proton linac (TRASCO-AC) consists of: an 80 kV ECR source; an RFQ up to 5 MeV; a superconducting linac with independently-phased cavities (either of reentrant type, quarter-wave or half-wave resonators) up to 80-100 MeV; and finally a 3 section superconducting linac with elliptical multi-cell cavities up to 1 GeV. Several key components of the proposed linac have been built and tested. The main achievements and the activities planned for TRASCO_AC are briefly outlined.

"Spoke Workshop"

Los Alamos, 7-8 October 2002

Status of the High Current Proton Accelerator for the TRASCO Program

Paolo Pierini

INFN Milano - LASA

on behalf of the TRASCO_ACC group

TRASCO_ACC

D. Barni[a], G. Bellomo[a], G. Bisoffi[b], A. Bosotti[a], L. Celona[c], A. Chincarini[d], G. Ciavola[c], M. Comunian[b], A. Facco[b], S. Gammino[c], G. Gemme[d], G. Lamanna[e], A. Lombardi[b], P. Michelato[a], M. Napolitano[f], C. Pagani[a], A. Palmieri[b], R. Parodi[d], P. Pierini[a], A. Pisent[b], F. Scarpa[b], D. Sertore[a], V. Zviagintsev[b],

[a]INFN Milano LASA	http://wwwlasa.infn.it
[b]INFN-LNL	http://www.lnl.infn.it
[c]INFN-LNS	http://www.lns.infn.it
[d]INFN Genova	http://www.ge.infn.it
[e]INFN Bari	http://www.ba.infn.it
[f]University and INFN, Napoli	http://www.na.infn.it

INFN Istituto Nazionale di Fisica Nucleare

The TRASCO Program

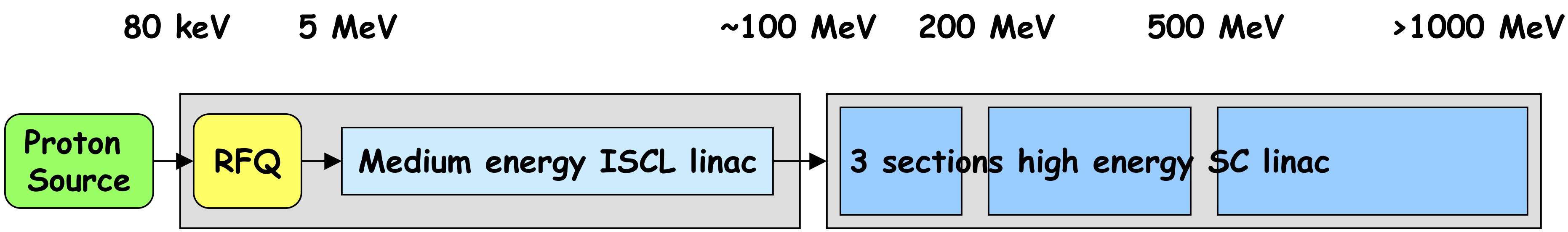
TRASCO: **conceptual study** and the **prototyping of components** for an **accelerator driven system for nuclear waste transmutation**, and involves research agencies and Italian companies

- TRASCO/ACC
  - **Accelerator studies**: lead by INFN
- TRASCO/SS
  - **Subcritical reactor** studies: lead by ENEA

TRASCO/ACC (1998-2004, in three funding stages) is devoted to:

- Conceptual design of a high current superconducting proton linac
  - **I=30 mA, E = 1 GeV**
- Construction and R&D activities on key items:
  - an 80 kV, 35 mA proton source (**INFN - LNS**)
  - a 5 MeV, 30 mA, CW RFQ (**INFN - LNL**)
  - SC cavity prototypes for low β cavities (<100 MeV) (**INFN - LNL**)
  - SC cavity prototypes for β = 0.47 elliptical cavities (**INFN - MI**)
  - SC cavity prototypes for β = 0.85 sputtered cavities (**INFN - GE**)
  - engineering of elliptical SC linac components (cryomodules, etc.) (**INFN - MI**)

The Reference Linac Design



Source	RFQ	ISCL	High Energy SC Linac
Microwave RF Source High current (35 mA) 80 keV	High transmission 95% 30 mA, 5 MeV (352 MHz)	5 - 85/100 MeV SC linac Baseline design: Reentrant cavities (352 MHz) Alternative design: Spoke, $\lambda/2$, $\lambda/4$, ladder $8\beta\lambda$ FODO focussing with sc magnets	3 section linac: - 85/100 - 200 MeV, β=0.47 - 200 - 500 MeV, β=0.65 - 500 – 1000/2000 MeV, β=0.85 Five(six) cell elliptical cavities Quadrupole doublet focussing: multi-cavity cryostats between doublets - 704.4 MHz

TRIPS: TRASCO Intense Proton Source

High intensity (tens mA) proton sources exist, but ADS asks for high reliability and availability

Additional efforts are required for:

- Voltage and current stability
- Control of the low beam emittance

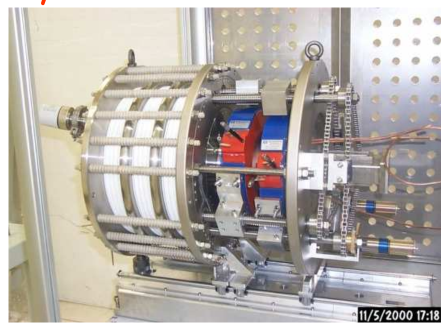
Design in 1999, source in LNS in May 2000

Achievements:

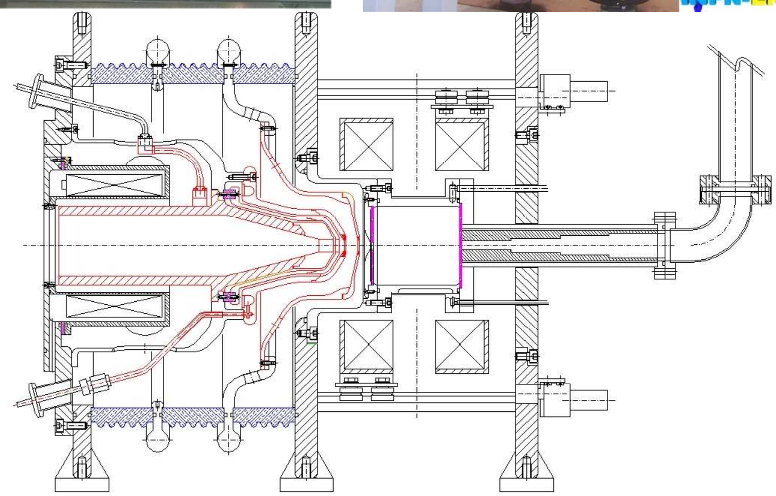
- First beam of 20 mA @ 60 kV in Jan 2001
- 80 kV, 55 mA operation in Aug 2001

Off-resonance microwave discharge source (2.45 GHz), based on SILHI (CEA/Saclay)

- Pentode configuration with new geometry
- Lowered voltage: from 95 kV to 80 kV



TRIPS Goals:		Achieved
Proton Beam current	35 mA	55 mA (~90% p.f.)
Beam emittance	0.2 π mm mrad	To be measured
Operating voltage	80 kV	80 kV



TRIPS recent performances

A rms emittance below 0.2 π mm mrad has been calculated with beam dynamics simulations, crosschecking different codes

- Emittance unit from CEA is being shipped to Catania for measurements

LEBT for beam analysis and characterization:

- Solenoid (focussing)
- Beam alignment monitor
- 2 current transformers for beam current measurements
- 10 kW beam stop

Reliability tests have been performed:

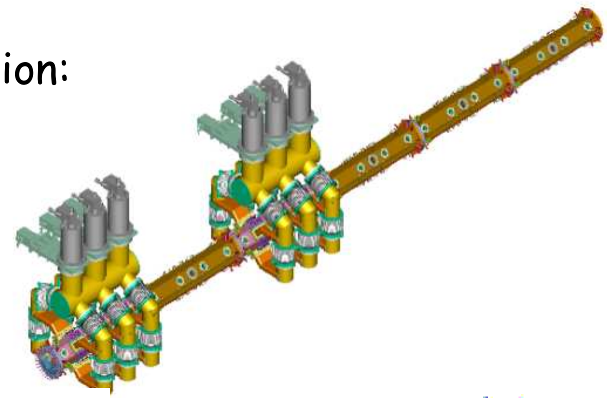
- **at 65 kV/15 mA: 24 h with no beam interruptions**
- **Tests at 80 kV are underway (improving)**

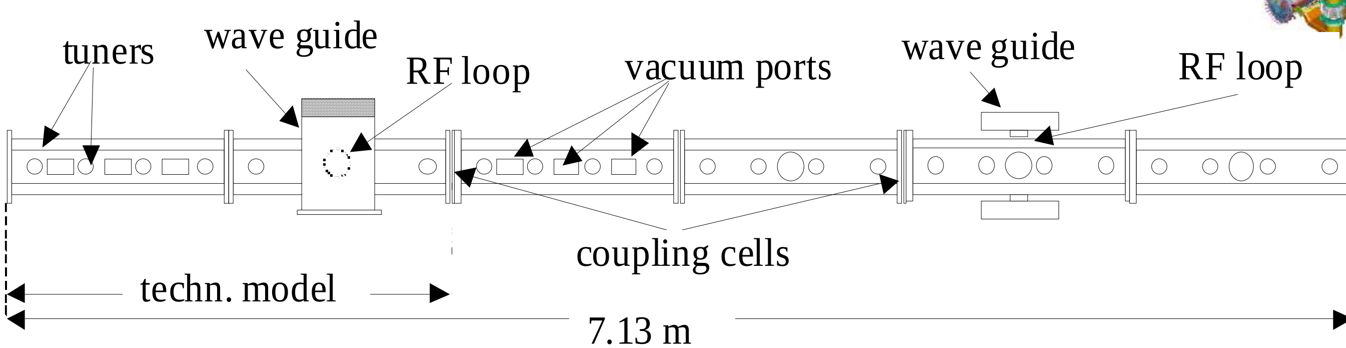
A new control system for automatic restart procedures after discharge is being implemented

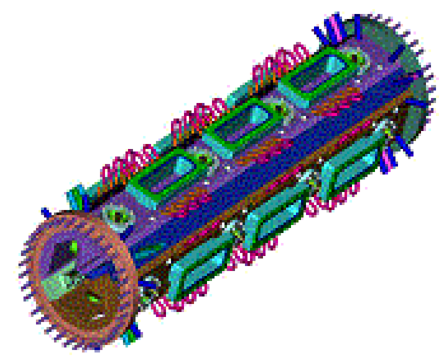
Low Energy Linac

The low energy linac is split in two components:

- A normal conducting CW Radio Frequency Quadrupole (RFQ): from 80 keV to 5 MeV
  - RFQ design: 3 resonantly coupled segments. Modulation:
    - Radial match in the structure
    - Shaper
    - Gentle buncher (from dc to 352.2 MHz bunches)
    - Accelerator (boosts up to 5 MeV, longest portion)







- A superconducting linac (ISCL): from 5 MeV to 100 MeV
  - Reentrant cavities for highest availability (allowing beam on with 1 cavity off)
  - $\lambda/4$, $\lambda/2$ cavities
  - Spoke cavities

RFQ Design and Fabrication tests

Laboratori Nazionali di Legnaro

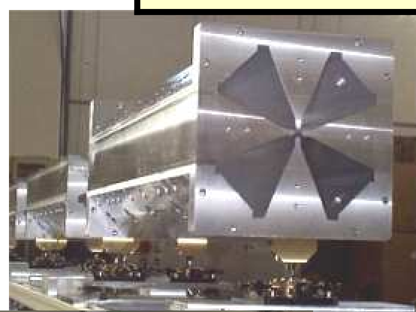
Different optimization procedure for TRASCO RFQ w.r.t. LEDA
- Limit to 1 RF source (1.3 MW CERN-LEP klystron)
- Lower current of 30 mA (96 % transmission)
- Peak surface electric field is 33 MV/m, (1.8 Kp)
- Simplified engineering/manufacturing choices

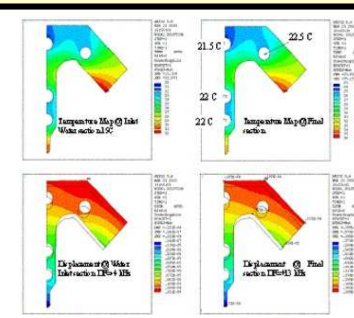
Substantial heat dissipation in the structure ~ 600 kW total

Three resonantly coupled segments

TRASCO RFQ:	
Beam current	30 mA (96 % transmission)
Beam emittance	0.2 π mm mrad T
	0.18 π deg MeV L
Final Energy	5 MeV
Length	7.13 m (3 sections)
RF Power	150 kW (beam)
	600 kW (structure)
Peak Field	1.8 Kilpatrick

A 3 m Al model of the structure has been built and measured at LNL, and achieved the necessary field stabilization





A 220 mm part of the structure has been built to test the full fabrication procedures
- Brazing
- Water channels by long (1 m) drilling

Full structure is under fabrication

Superconducting low energy linac

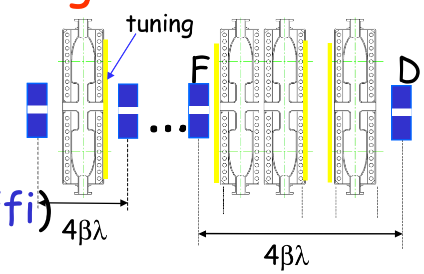
Laboratori Nazionali di Legnaro

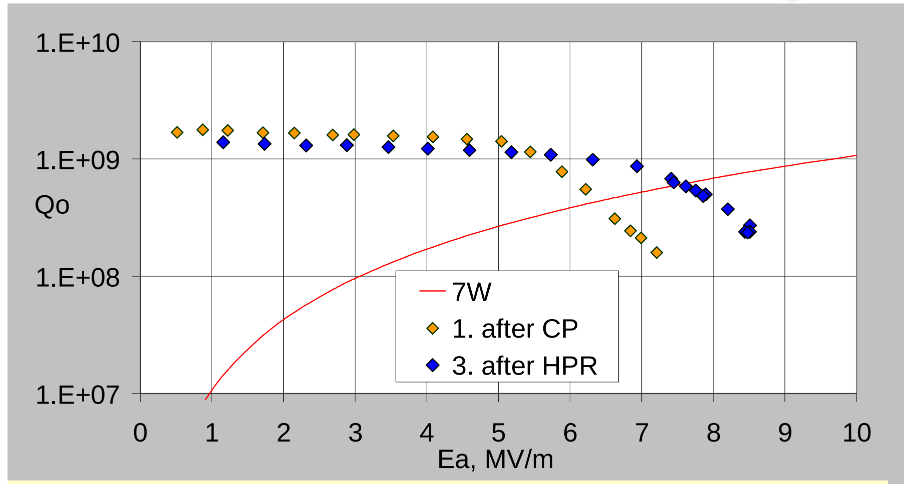
Single or two-gap structure linac

- Moderate energy gain/cavity
- Solid state RF amplifiers
- 8 $\beta\lambda$ focussing lattice

Various options, are being considered

- Reentrant cavities
- Spoke cavities
- $\lambda/4$ cavities
- Ladder (see G. Bisoffi)





See A. Facco talk (13:40 October 8)

Quarter Wave resonator (QWR) 2 gap structure of the ALPI linac in INFN-LNL

2 gap spoke cavity

Reentrant cavity single gap structure.
He Vessel integrated in the cavity

The high energy linac

Conceptual design of the 3 section linac

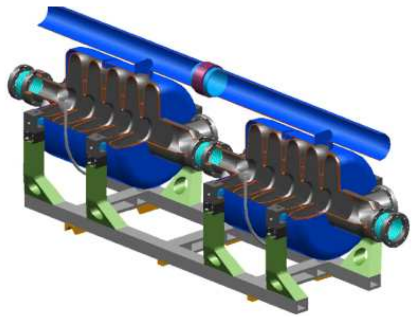
Development and test of prototype cavities

- At 352 MHz with the LEP II sputtering technology
- At 704 MHz, bulk niobium, for the lowest β

Design and engineering of cavity components and ancillaries

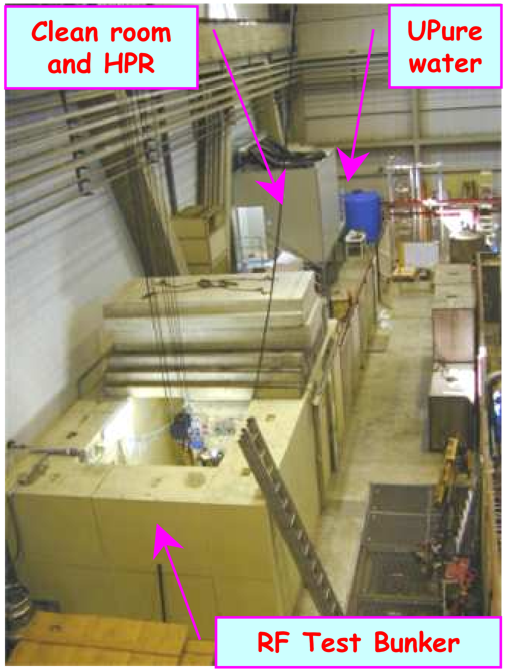
- Cryomodule, tuner system, piezo damping, …

RF Test infrastructure



Designed with high current beam dynamics criteria to avoid emittance growth (smooth, tune resonances, ...)

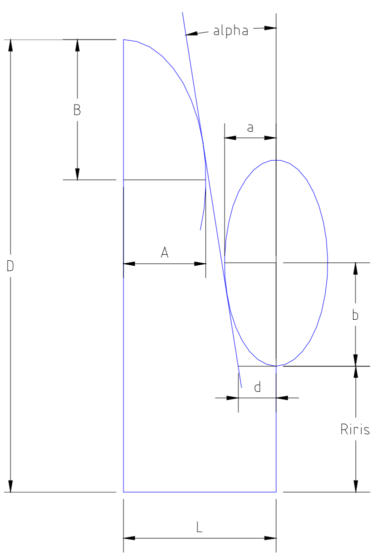
Section β	0.47	0.65	0.85
# cells/cavity	5	5	6
Length	50 m	93 m	102 m
Initial/Final Energy	100 MeV	190 MeV	480 MeV
	190 MeV	480 MeV	1 GeV
Doublet period	4.2 m	5.8 m	8.5 m
# periods	12	16	12
# cavities in section	24	48	48
Max. Eacc (MV/m)	8.5 MV/m	10.2 MV/m	12.3 MV/m

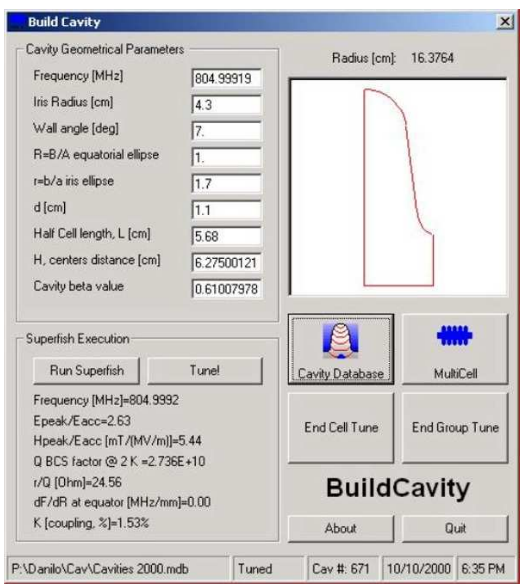


Conceptual design: cavity & linac design

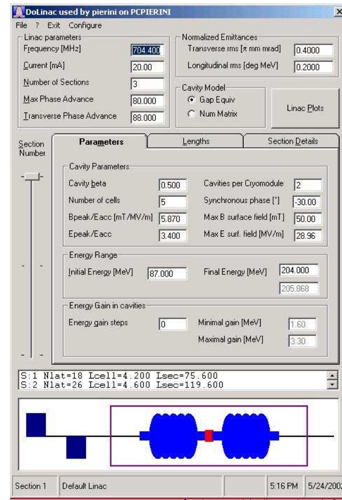
INFN Milano LASA

- Parametric tool for the analysis of the cavity shape on the electromagnetic (and mechanical) parameters
  - Inner cell tuning is performed through the diameter, all the characteristic cell parameters stay constant: R, r, α, d, L, Riris
  - End cell tuning is performed through the wall angle inclination, α, or distance, **d**. R, L and Riris are set independently
  - End groups for a 4 die cavity tuned using the end cell diameter (and α,d,R,L, Riris are indep. set)

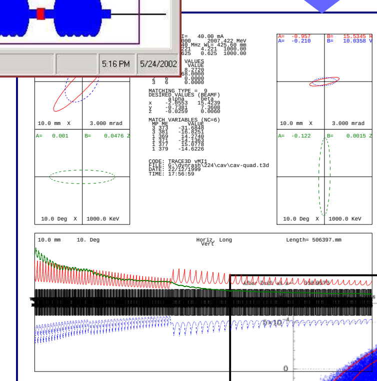




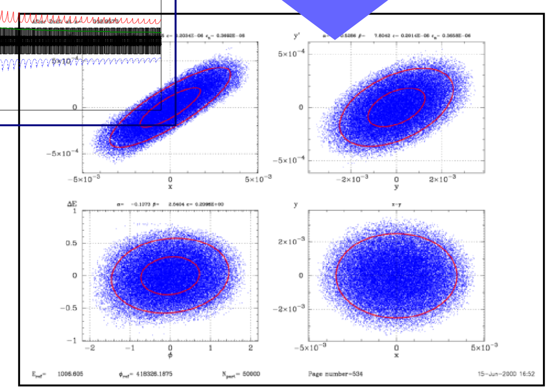
Build linac from **simple rules**, with **control of longitudinal & transverse phase advances**



Find **matched beam** solution in all linac



Run non-linear multi-particle simulations for confirmation of design



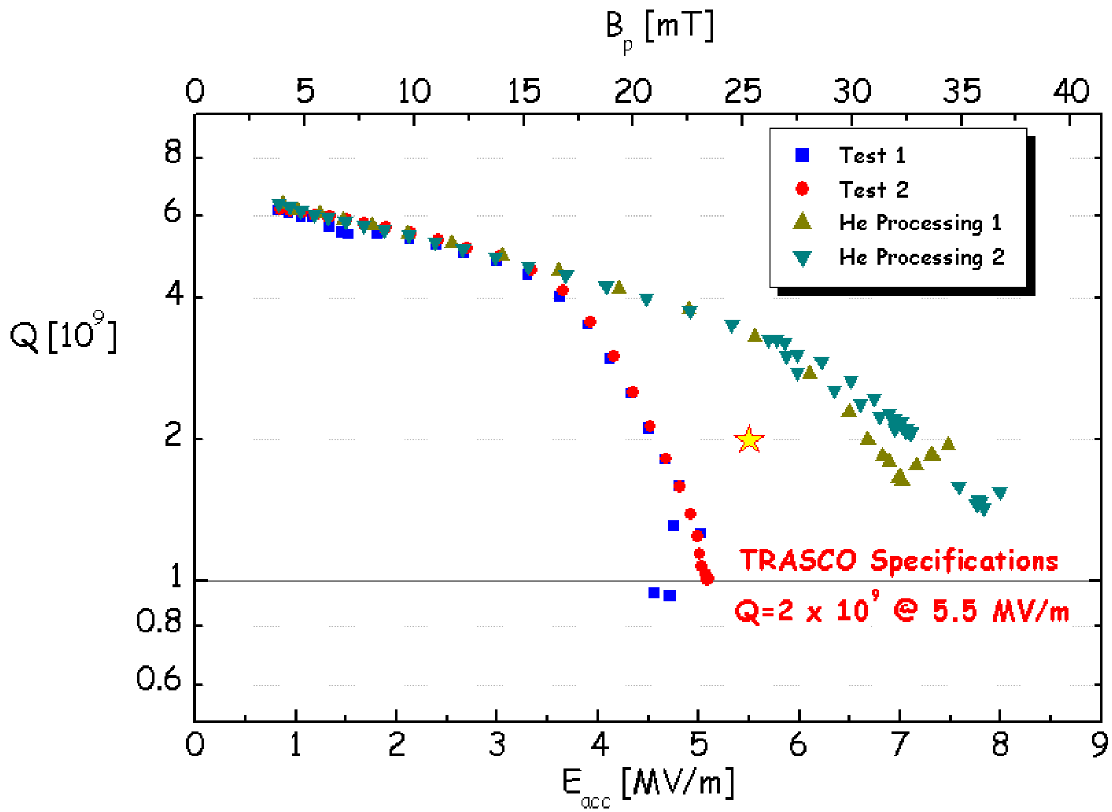
352 MHz β=0.85 prototypes with CERN

352 MHz cavities with CERN (MOU)

- Use LEP II sputtering technology
- Single cell and 5 cell sputtered – $\beta = 0.85$
- Cavity integrated in a LEP type cryostat

All tests reached the design goals, indeed performed as the best LEP batch

But: Bulk niobium is needed at lower β, and the gradient is moderate w.r.t 704 MHz



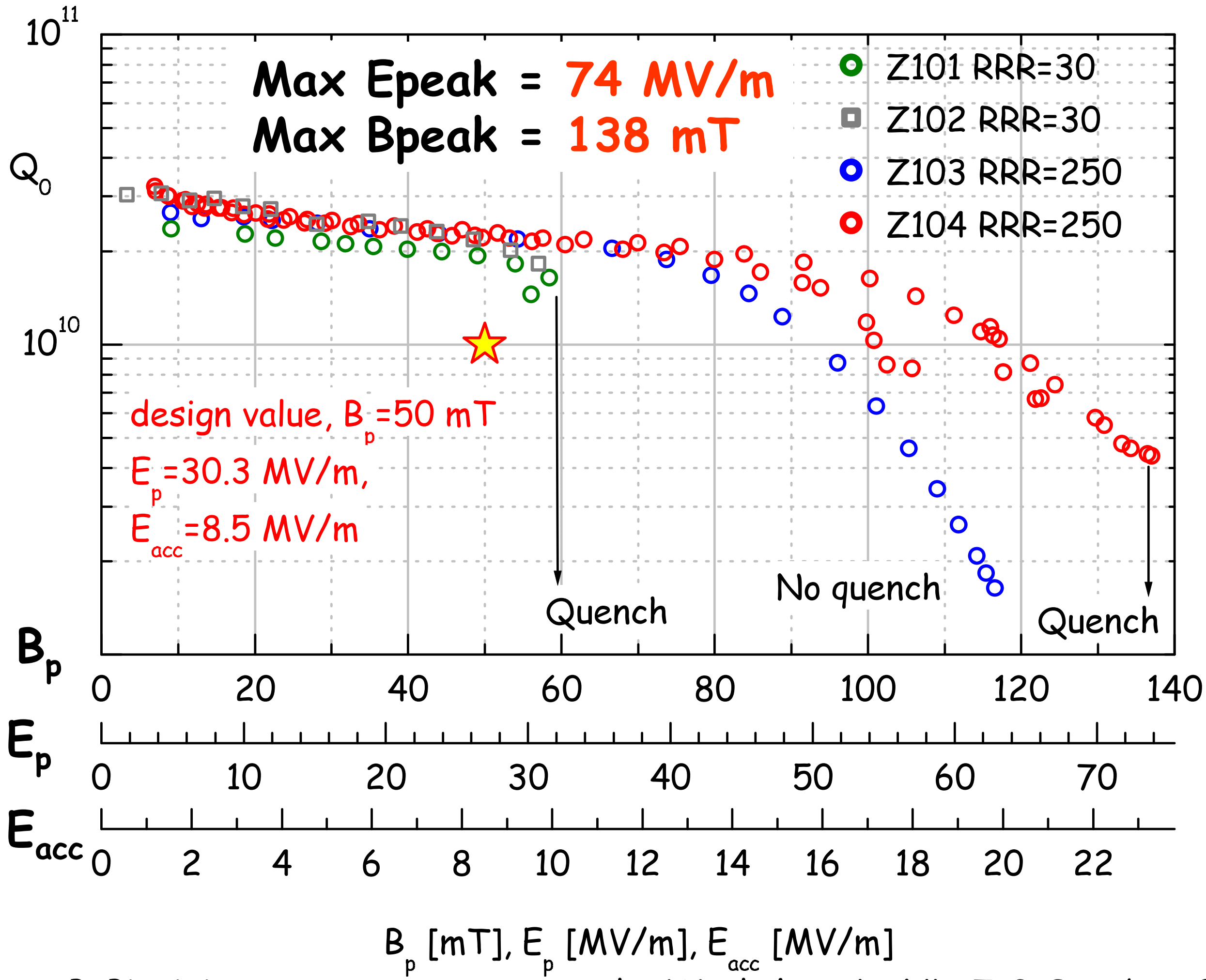
Test in a modified LEPII cryomodule (Aug. 2001)

- Powered to 250 kW
- 7 MV/m

β=0.47 single cell cavities prototypes

Fabricated with RRR>30 & RRR>250 Niobium at Zanon

BCP, HPR and tests at TJNAF (Z104) and Saclay (Z101-Z103)



For 1-cell:

E_p/E_{acc} = 2.90

B_p/E_{acc} = 5.38 mT/(MV/m)

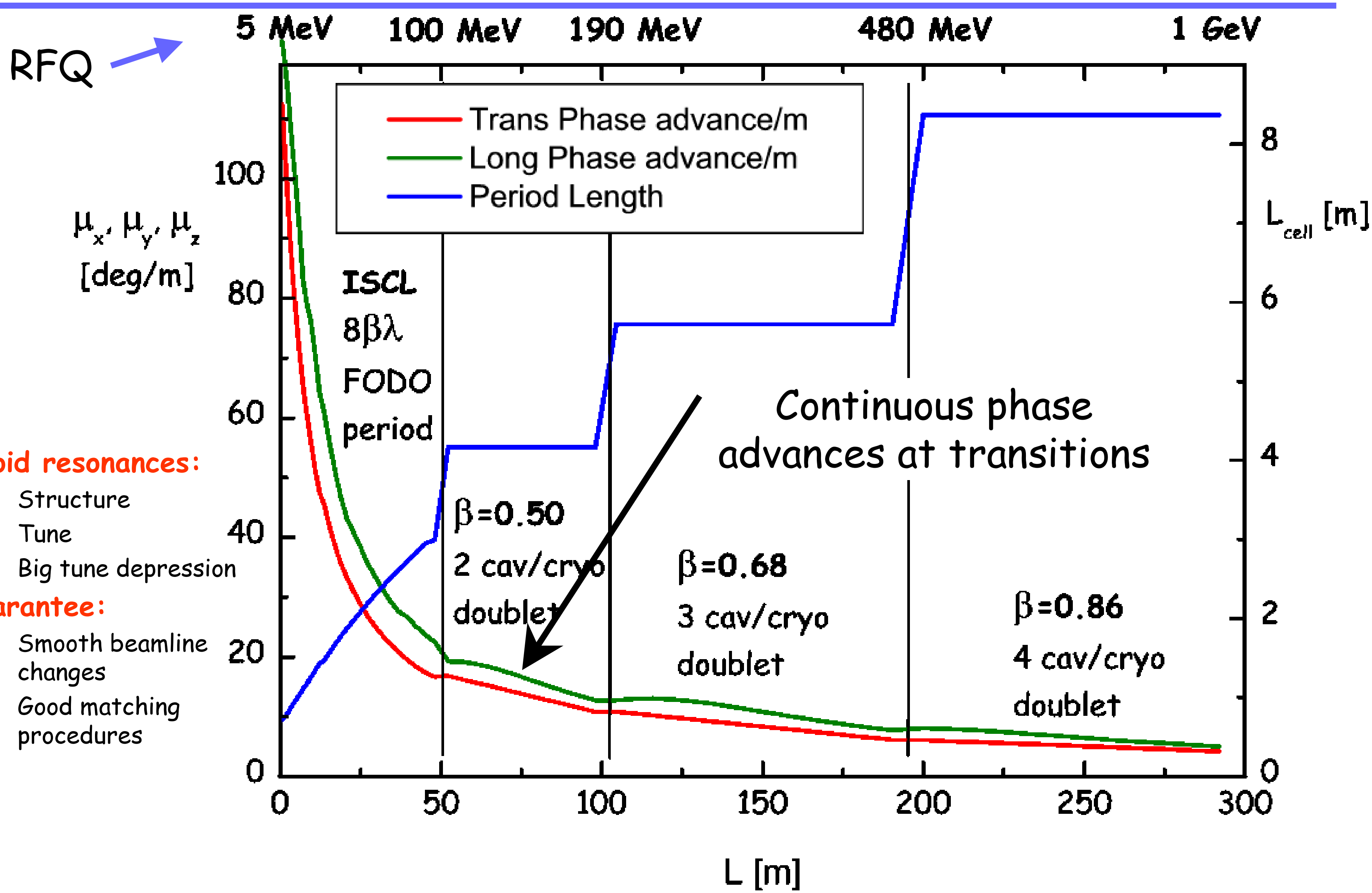
For 5-cell:

E_p/E_{acc} = 3.57

B_p/E_{acc} = 5.88 mT/(MV/m)

Two 5 cell cavities are under fabrication at ZANON

Baseline of the "smooth" linac design

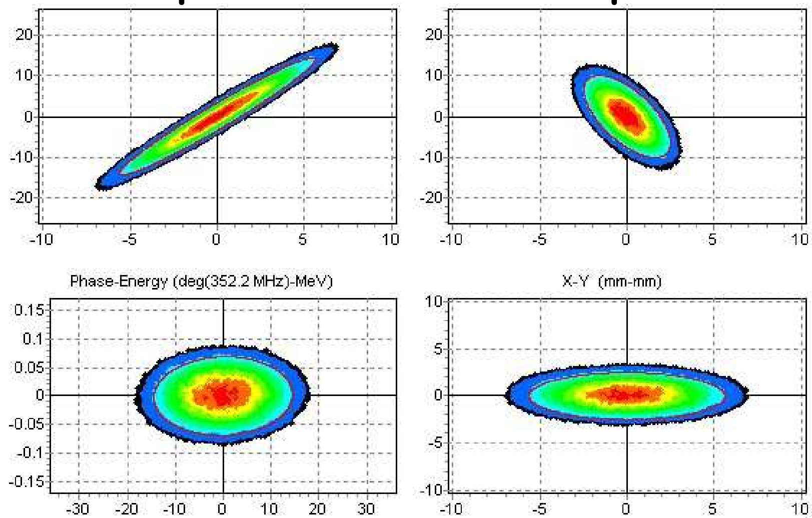


Avoid resonances:
- Structure
- Tune
- Big tune depression

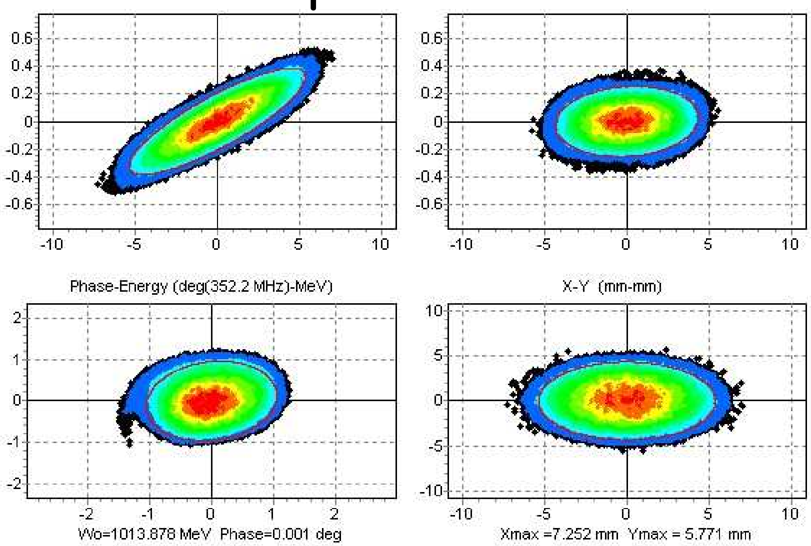
Guarantee:
- Smooth beamline changes
- Good matching procedures

Full SC linac from 5 MeV to 1 GeV

Input @ 5 MeV 10^5 ptcl

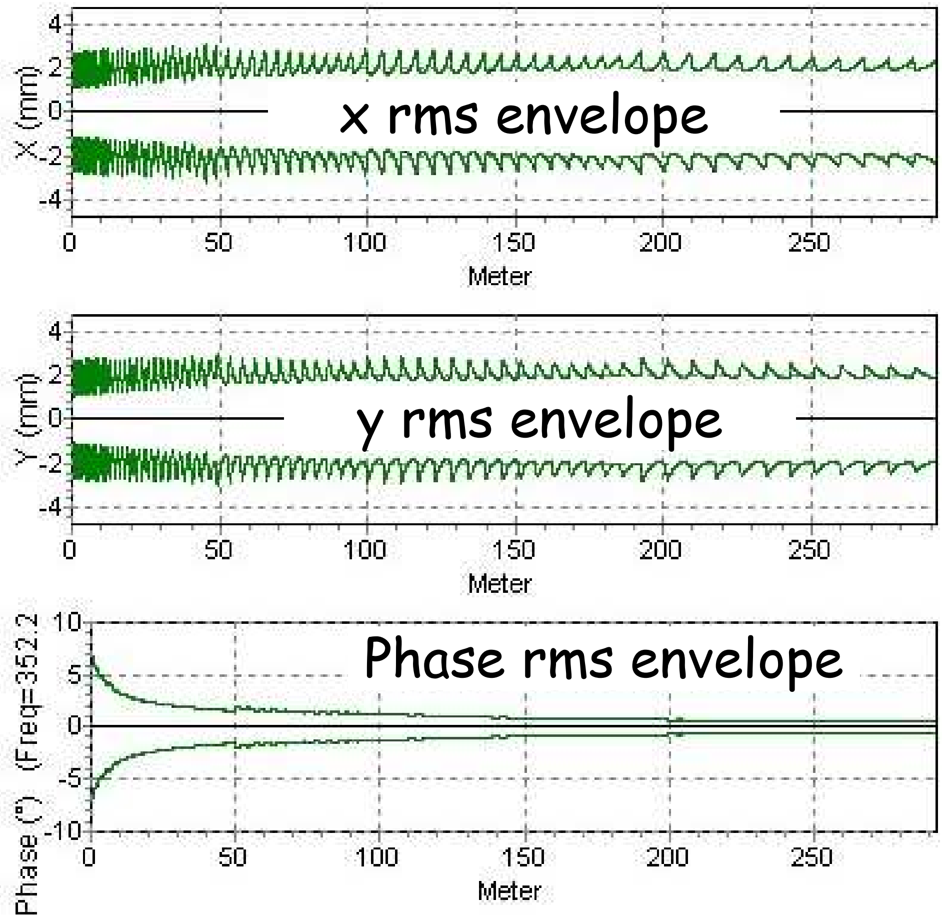


Output @ 1 GeV

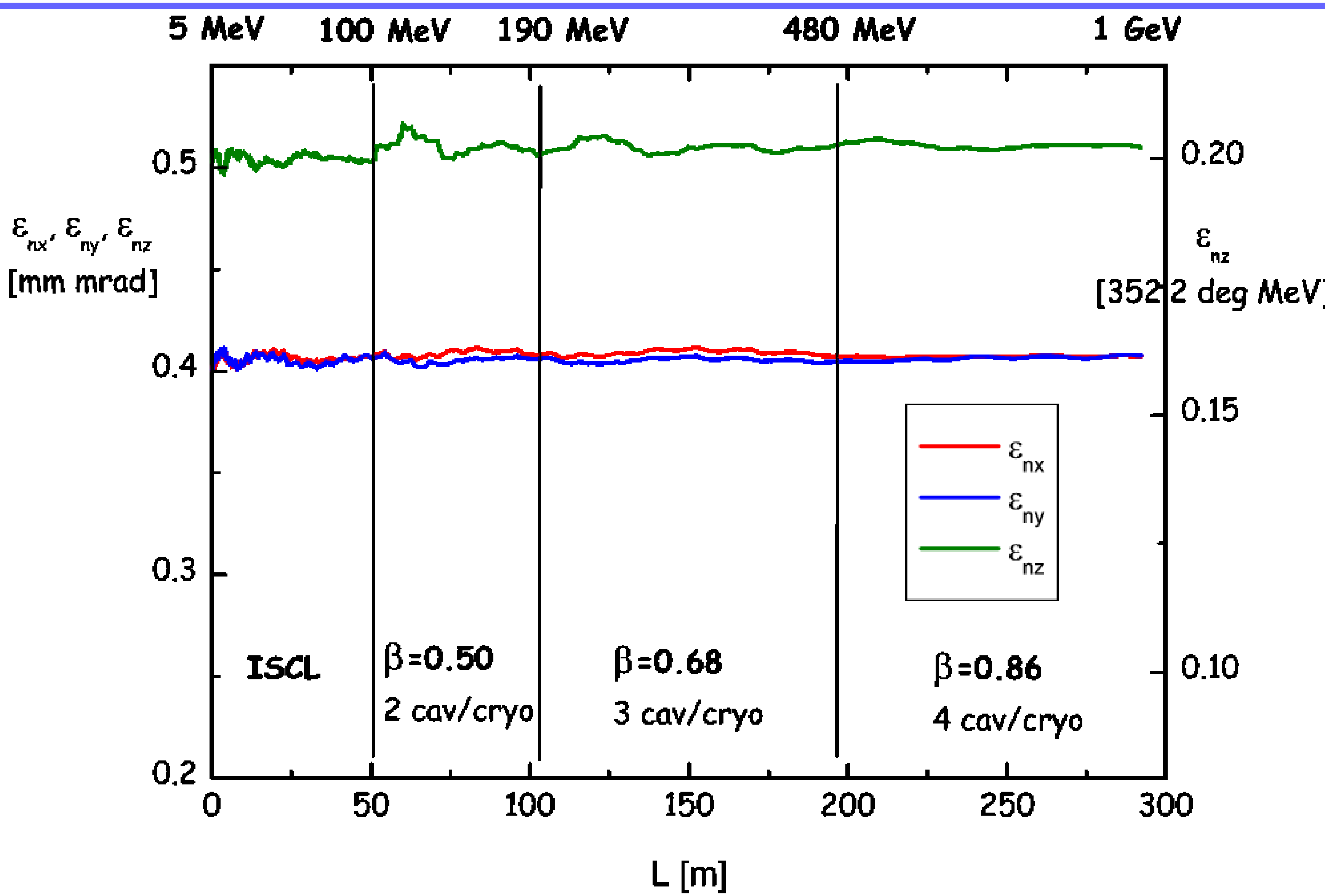


Results of non-linear simulations

No particle losses, beams well confined



Rms emittances growth (from end of RFQ to full energy) < 2%



Perspectives

The effort to build a complete ADS system exceeds the capabilities (and the funding availability) of any national program like TRASCO

- TRASCO means to provide significant R&D and prototipical effort along the road to the design of a transmuter system
- cfr. "*A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration*", by the European Technical Working Group on ADS, April 2001 (available in http://itumagill.fzk.de/ADS/)

Already in the 5th Framework Program of the European Commission a Program has been funded: "**PDS-XADS – Preliminary Design Studies** for an e**X**perimental **Accelerator Driven System**"

- 25 Partners, from Research Institutions to EU Industries
- 12 M€ Program (50% supported by the Commission)
- Several Working Packages, dealing with various aspects of an ADS
- WP3 is dedicated to the Accelerator

More to come in the 6th Framework Program about to start …

Discussion on "Status of the high Current Proton Accelerator for the TRASCO Program" by Paolo Pierini

Discussion missing due to end of tape. Discussion mainly focused on single-cell vs 5-cell performance data for elliptical cavities.

Specific Designs

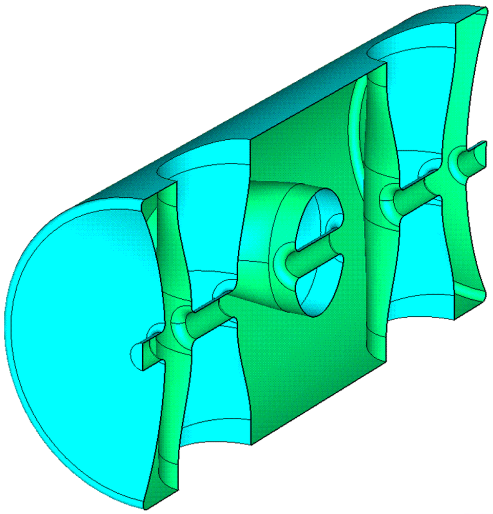
Ken Shepard: "*RIA Project: Spoke Cavity Design*"
(Abstract | Viewgraphs | Discussion)
Guillaume Olry: "*CNRS: XADS/Eurisol*"
(Abstract | Viewgraphs | Discussion)
Evgeny Zaplatin: "*Electrodynamics & Mechanics of Multigap Low-Beta SC Structures*"
(Abstract | Viewgraphs | Discussion)
Frank Krawczyk: "*RF Design of Spoke Resonators for the AAA Project*"
(Abstract | Viewgraphs | Discussion)
Giovanni Bisoffi: "*The Ladder Spoke Resonator at INFN Legnaro*"
(Abstract | Viewgraphs | Discussion)
All: "*General Discussion on RF-Design*"
(Discussion)

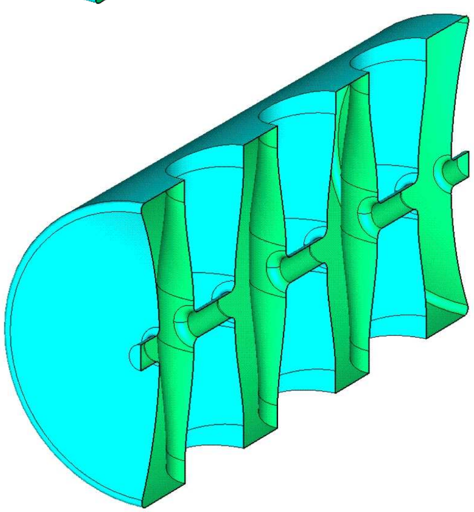
RIA Project: Spoke-cavity Design

K. Shepard, Argonne National Laboratory

Geometry and electromagnetic properties of 345 MHz multiple-spoke cavity designs for RIA are discussed. Mechanical details and current status of prototype multiple-spoke cavities are presented.

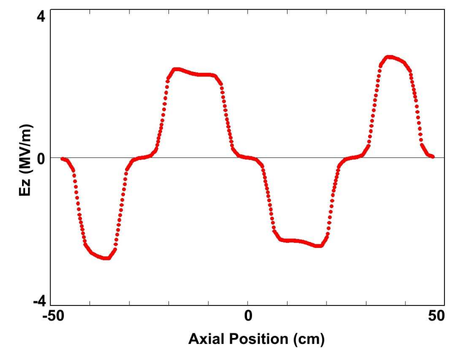
Crossed–spokes give better mode-splitting

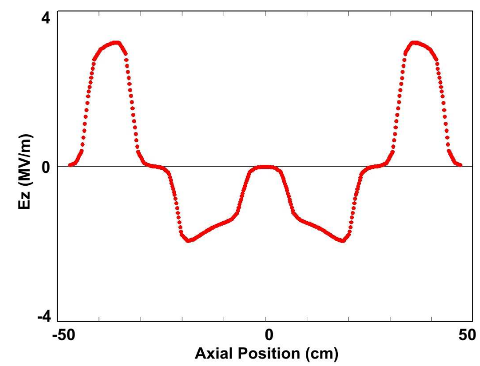




Eigenfrequency (MHz)		
Mode	**Crossed**	**Parallel**
1	345.2	345.2
2	362.3	347.4
3	397.8	364.8
4	442.1	412.1
5	476.1	438.3

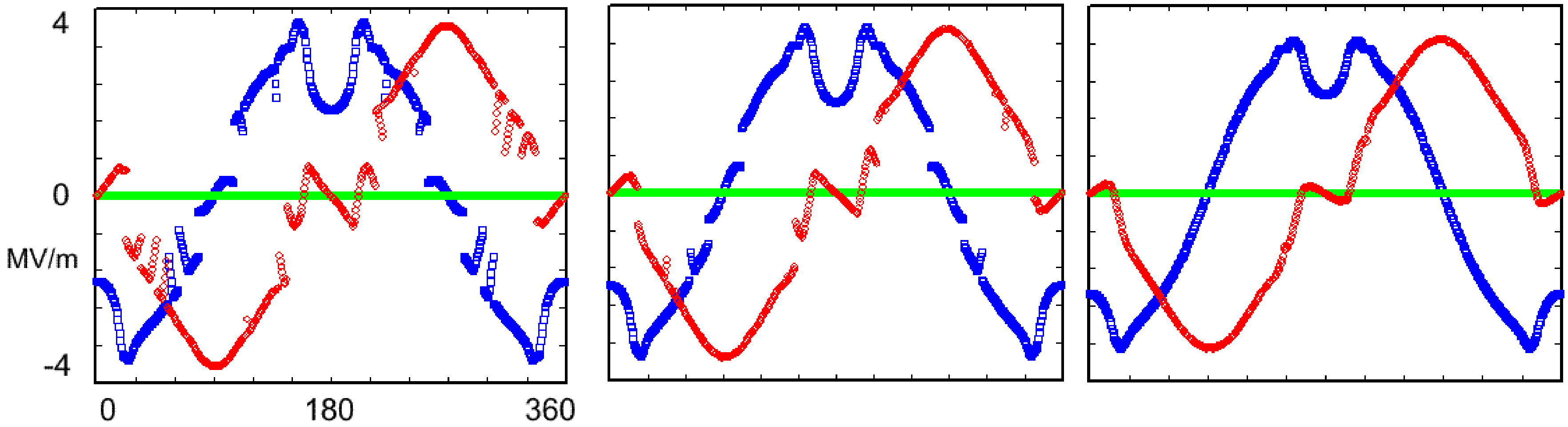
First Mode

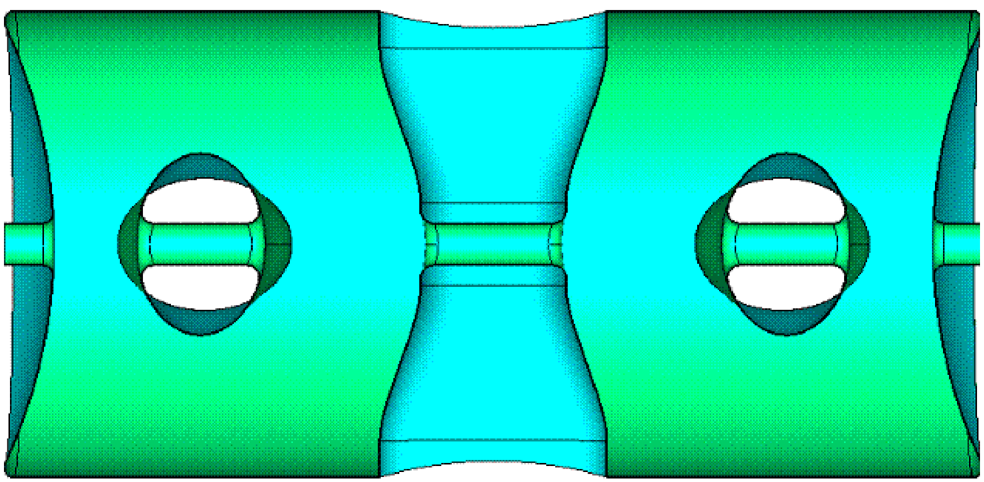




Second Mode

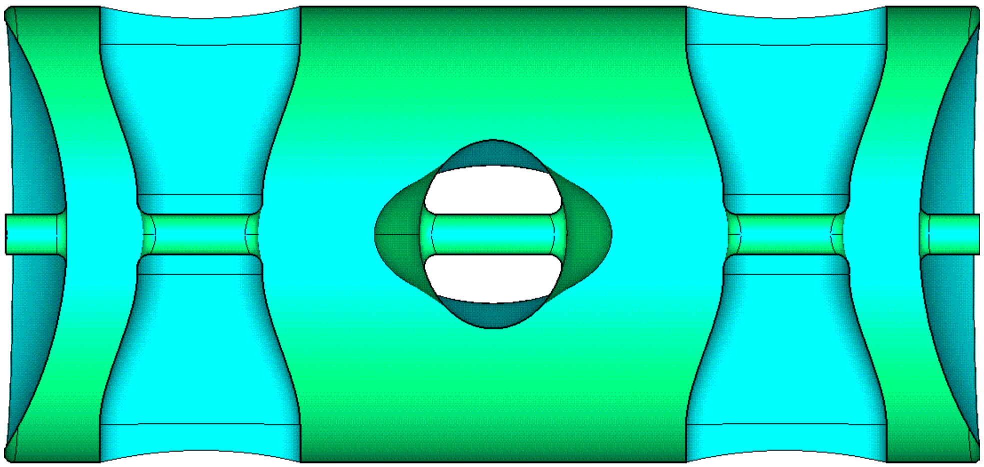
0 mm from surface 2 mm from surface 5 mm from surface

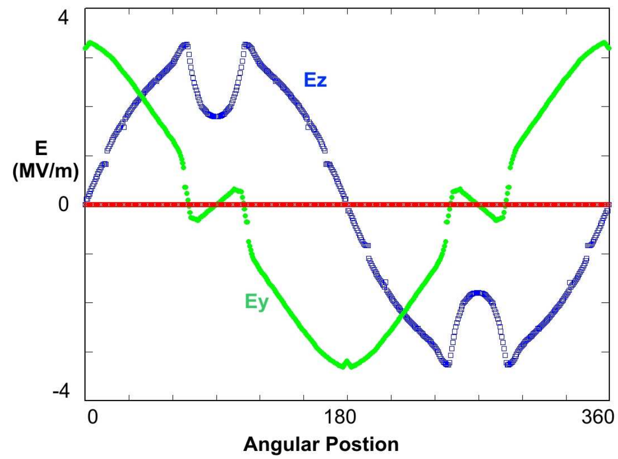




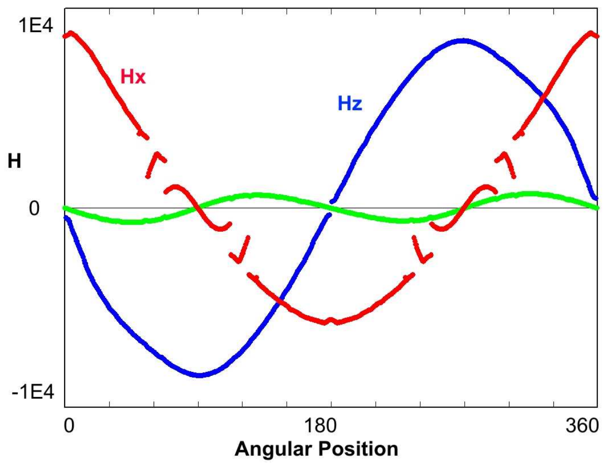
MWS results with a cell size of ~ 5 mm

4 cm beam aperture at 345 MHz is non-trivial, but feasible

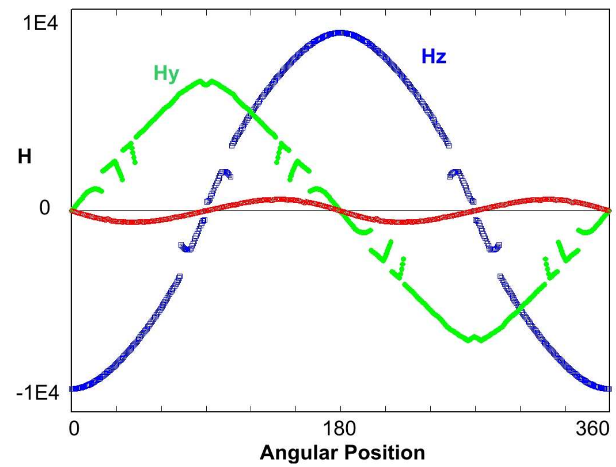




Center Spoke



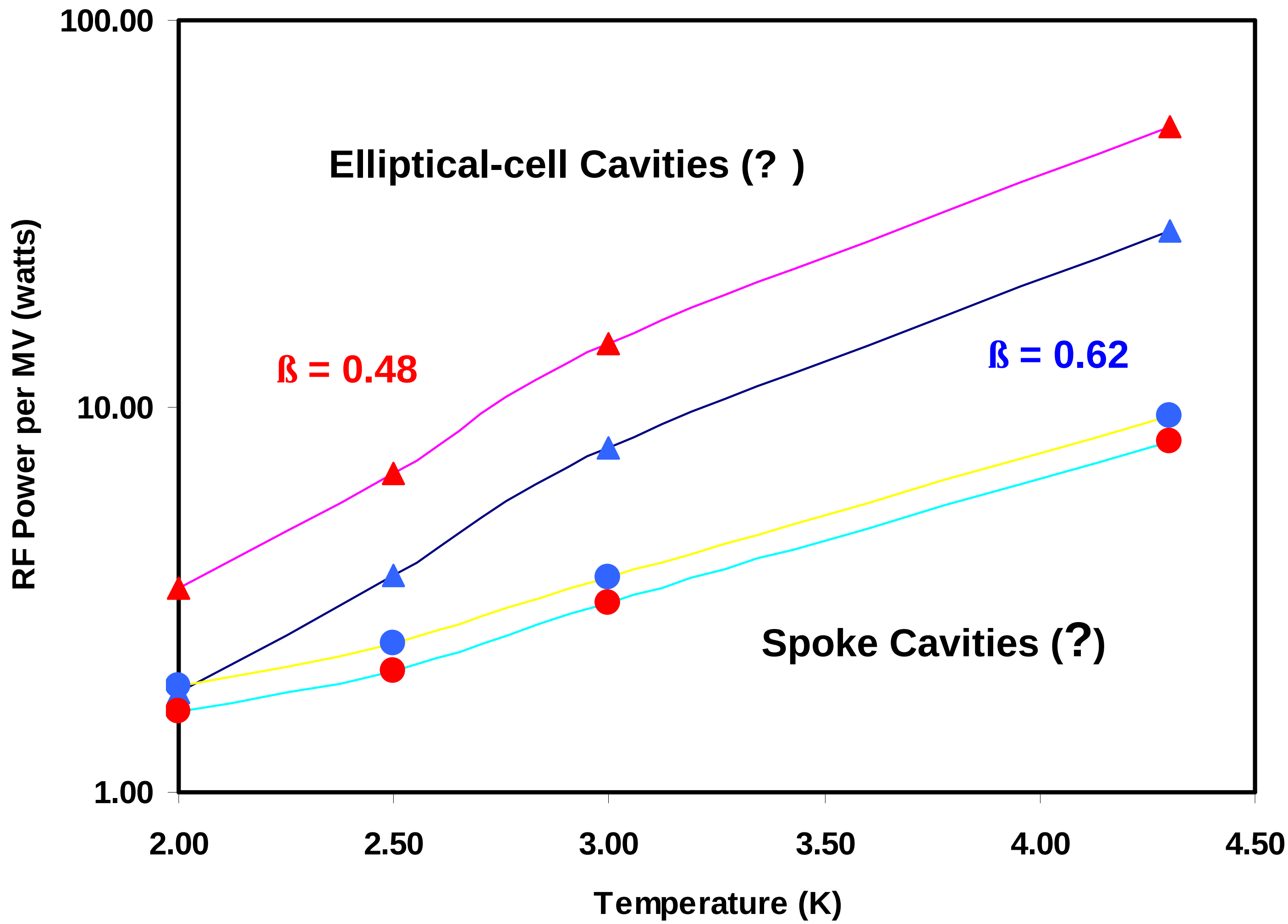
End spoke (base)



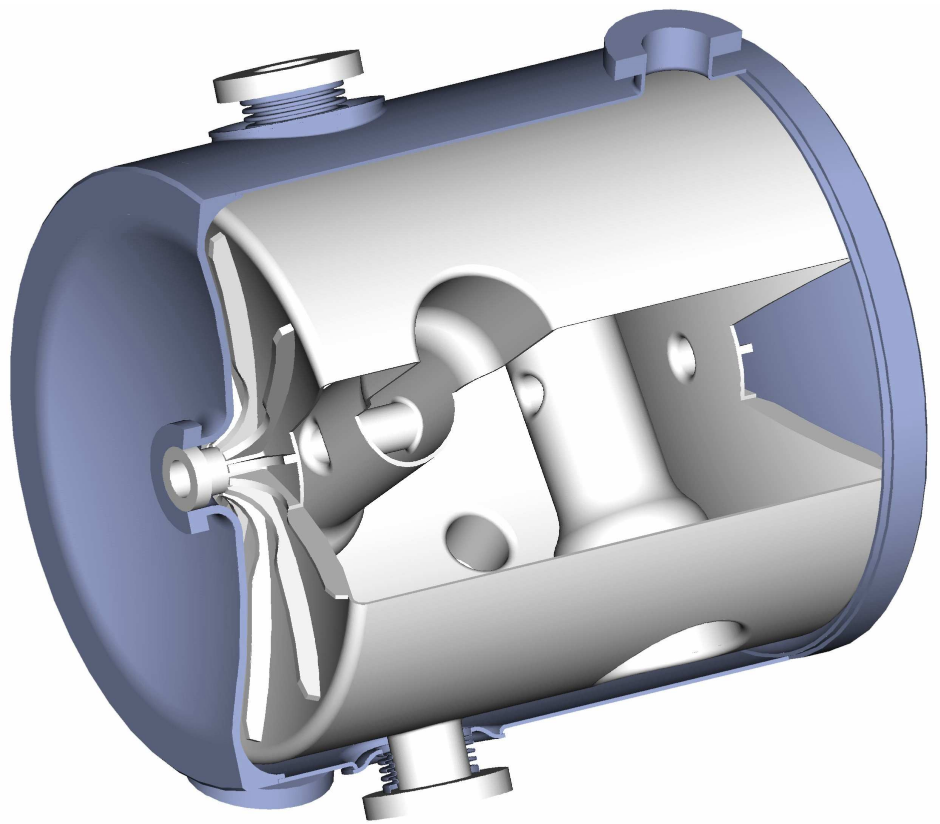
EM Parameters for a ß=0.62 triple-spoke cavity

	Present	Preliminary
Aperture	4 cm	3 cm
$ß_{GEOM}$	0.63	0.62
$L_{EFFECTIVE}$	85 cm	85 cm
Frequency	345 MHz	345 MHz
QR_S	106	103
€		
at 1 MV/m		
E_{PEAK}	2.73	3.1
B_{PEAK}	92	88
RF Energy	642 mJ	582 mJ

RF Loss into helium bath (assuming 10 nano-ohm residual resistivity)



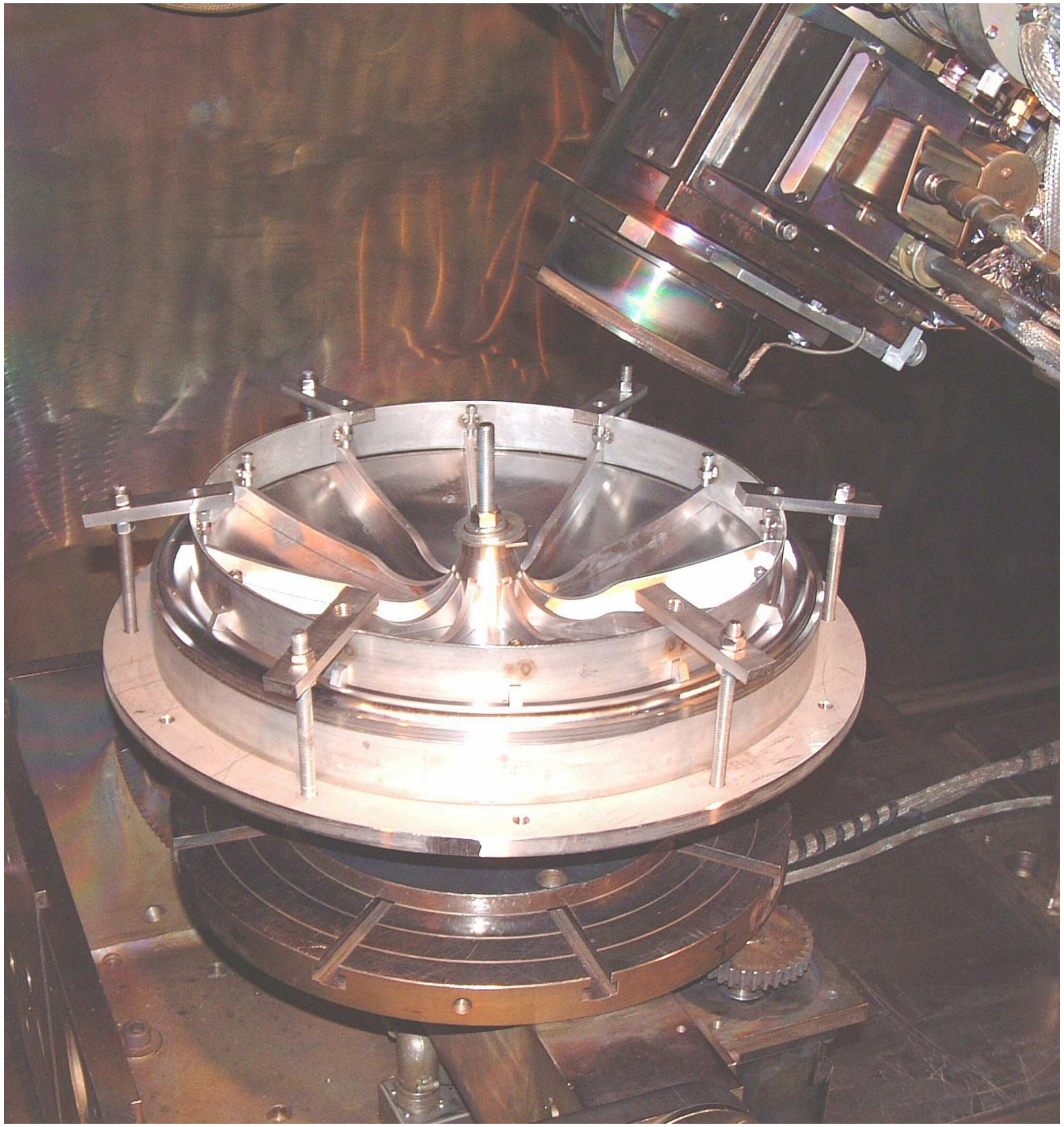
Stainless-steel helium jacket



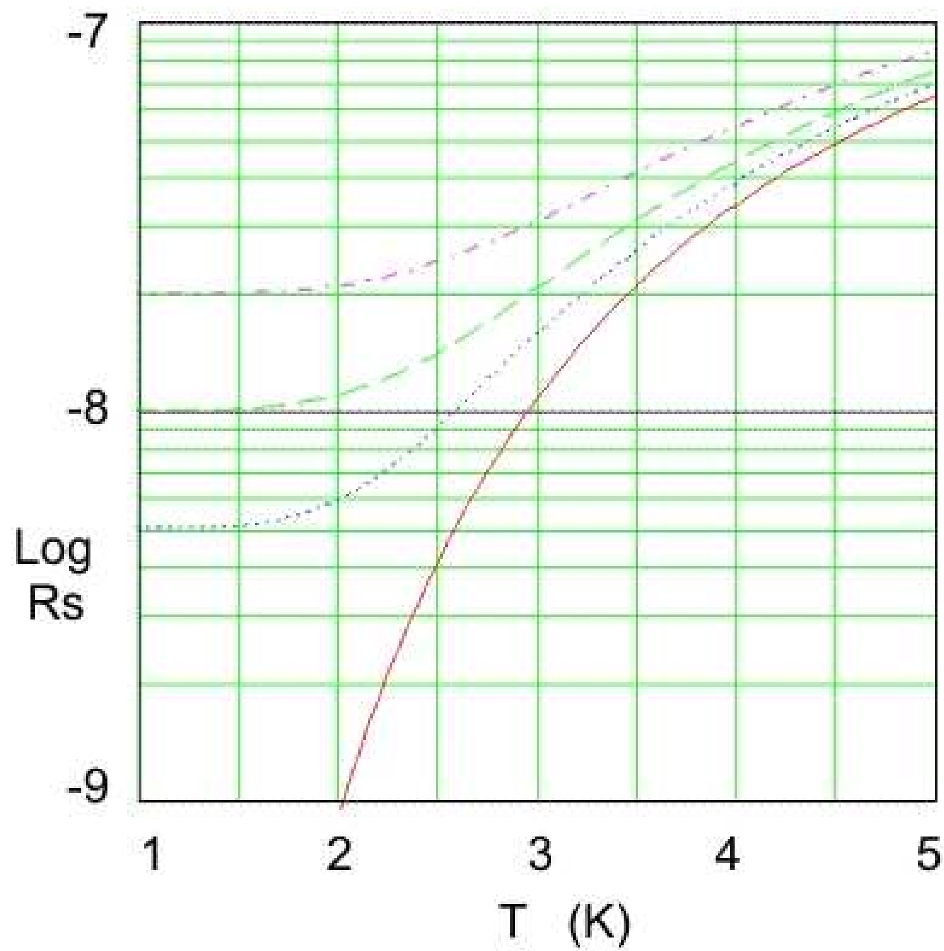
Major sub-assemblies of the double-spoke cavity

Pieces of the Double spoke prototype

Welding on 12 Support Gussets



R_s vs. Temperature at 345 MHz for 0, 5, 10, 20 nano-ohm residual resistivity



Discussion on "RIA Project: Spoke-cavity Design" by Ken Shepard

Part of the presentation focused on the comparison of elliptical and spoke resonators at different temperatures. The interpretation of some curves depended on the validity of the use of 10 nΩ as residual surface resistance. It was pointed out that this value is too high for elliptical cavities. Shepard showed that using a lower value for the comparison made the advantage for spokes only more obvious. Experimental data at LANL show that well cleaned spoke resonators can reach residual resistance as low as 8.5 nΩ.

In support for the validity of the comparison it was also pointed out that the comparison of 700 MHz elliptical cavities and 350 MHz spokes reflects their use in an accelerator. Also, this way cavities of similar dimensions are compared.

The design work presented also showed a comparison of cross-bar to parallel bar spoke cavities. Delayen pointed out that the result of comparable peak fields and shunt impedance is only valid for higher β spokes. For lower β spokes the cross-bar has been shown to be superior. Shepard explained that his major reason to disregard the parallel bar spokes is their poor mode splitting.

The stiffness of multigap spoke resonators brings up the question of their tunability. Shepard laid out the plan to measure frequencies before the final weld of the endcaps. Another step done before this weld and the tuning is an electropolish of the cavity parts. Delayen pointed out that the tuning will not be affecting the field flatness very much. The strong magnetic coupling of the cells will prevent this. Tuning will mostly affect the frequency. Final tuning after welding is mostly to compensate the effect of the polishing.

XADS/Eurisol

G. Olry, CNRS, IPN Orsay

RF design of the $\beta_g = 0.35$, 2-gap spoke cavity has been done with the MAFIA EM code. Starting from the so-called pillbox cavity model, optimization of the main parameters E_{peak}/E_{acc}, B_{peak}/E_{acc} and transit time factor, has led to specific shapes for the spoke bar (i.e. a cylindrical spoke base and a racetrack spoke center) and the reentrant end-walls (in order to maintain the ratio of 1/3 between the spoke bar dimensions and the cavity length). The different steps of the EM calculations are described.

RF design of the β0.35 spoke cavity "AMANDA"

Division Accélérateurs

Guillaume OLRY
Institut de Physique Nucléaire
olry@ipno.in2p3.fr

Introduction

European projects

- ***XADS*** (Transmutation) : CW, I=10 mA (→40 mA), E=600 MeV (→1 GeV)
- ***EURISOL*** (Radioactive ions beams) : CW, I=5 mA, E=1 GeV (→2 GeV)

Study of spoke cavities

5…10 MeV (β_p~0.1) < E_{proton} < 80…100 MeV (β_p~0.5)

IPHI injector

ECR source + RFQ

Elliptical cavities

5-cell, 700MHz

RF design

Main parameters

- Frequency: 352 MHz

  IPHI frequency

  Large beam tube aperture

- 2-gap cavity

  Fabrication cost

  Higher energy acceptance/multi-gap cavities

- β_g=0.35

  Transition with β0.47 elliptical cavities (~85 MeV)

Geometry optimization

- Many parameters

  Spoke bar shape (base & center)

  End walls

- Minimize Ep/Eacc & Bp/Eacc

- Maximize Eacc and T

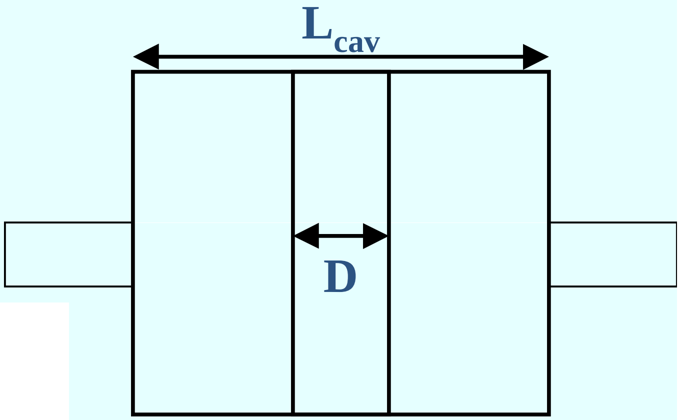
- "Simple" final geometry

  Feasibility

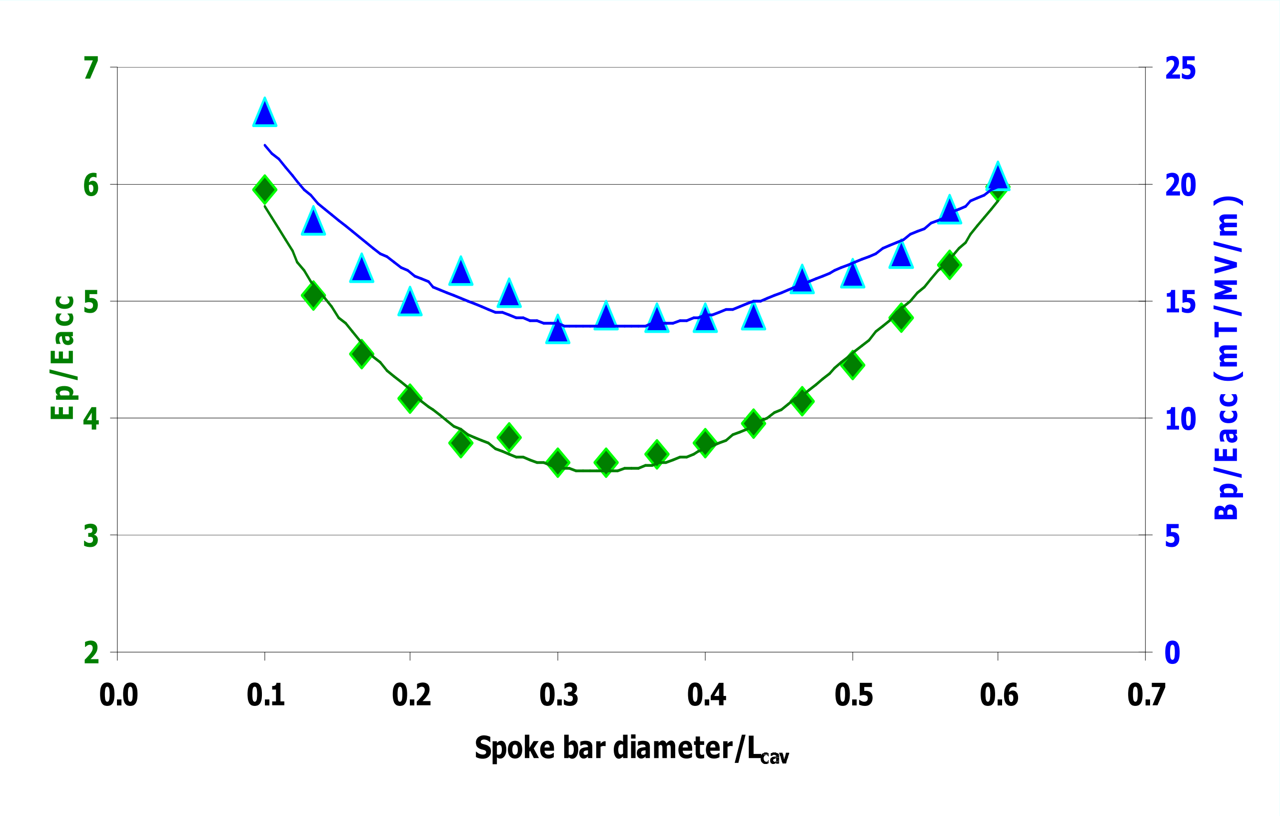
  Fabrication cost

RF design

Starting point : pillbox cavity with cylindrical spoke bar



- Variation of the spoke bar diameter (L_{cav} fixed)
- L_{cav}=300 mm, Cavity diameter=300 mm

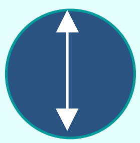
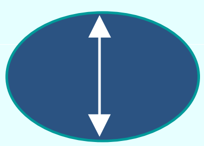
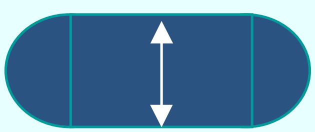


Minimum for $D/L_{cav}=1/3$

RF design

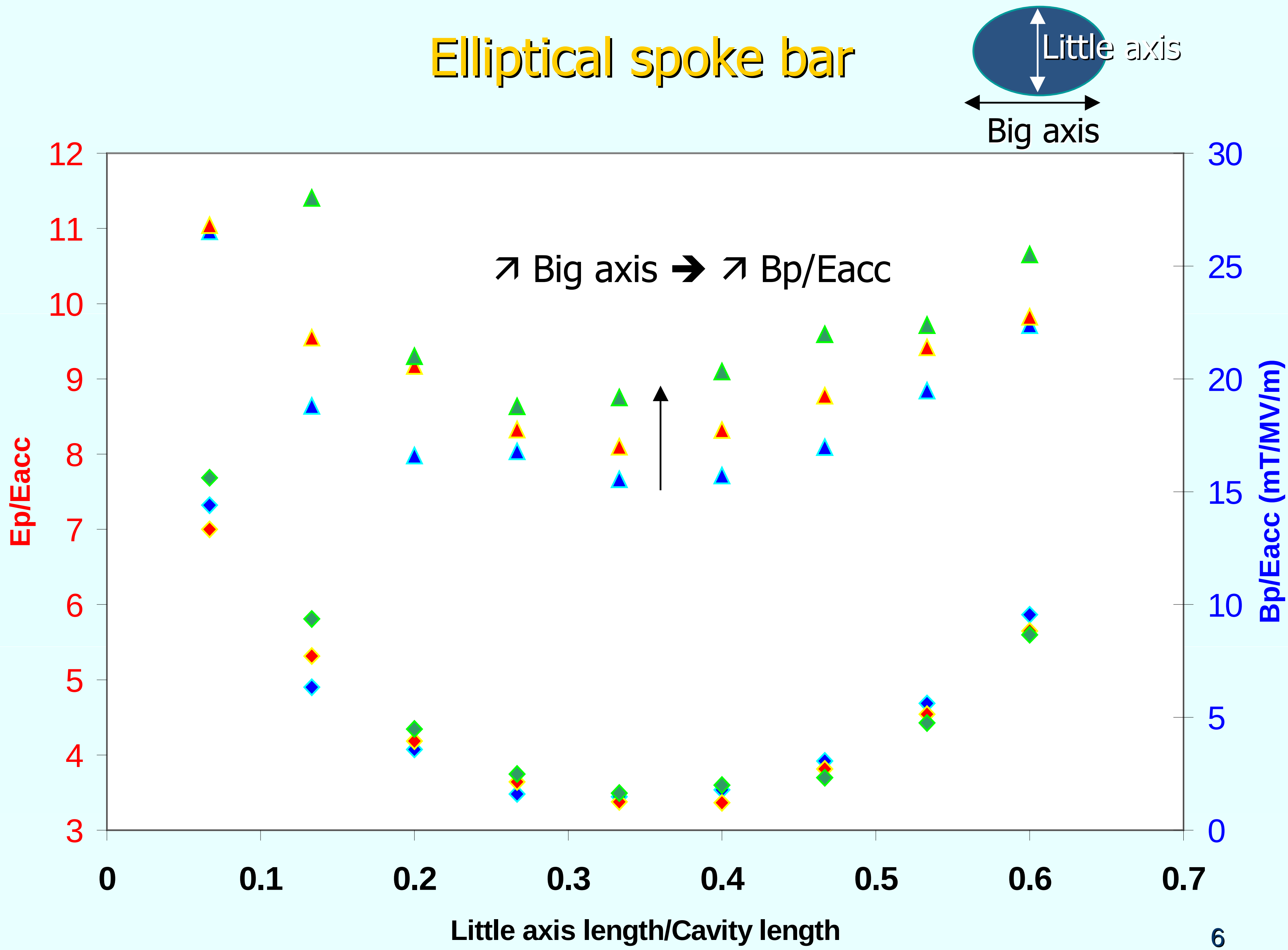
Comparison : cylindrical, elliptical and racetrack spoke bar shape

- Mesh points : 1 000 000, mesh size : 2 mm

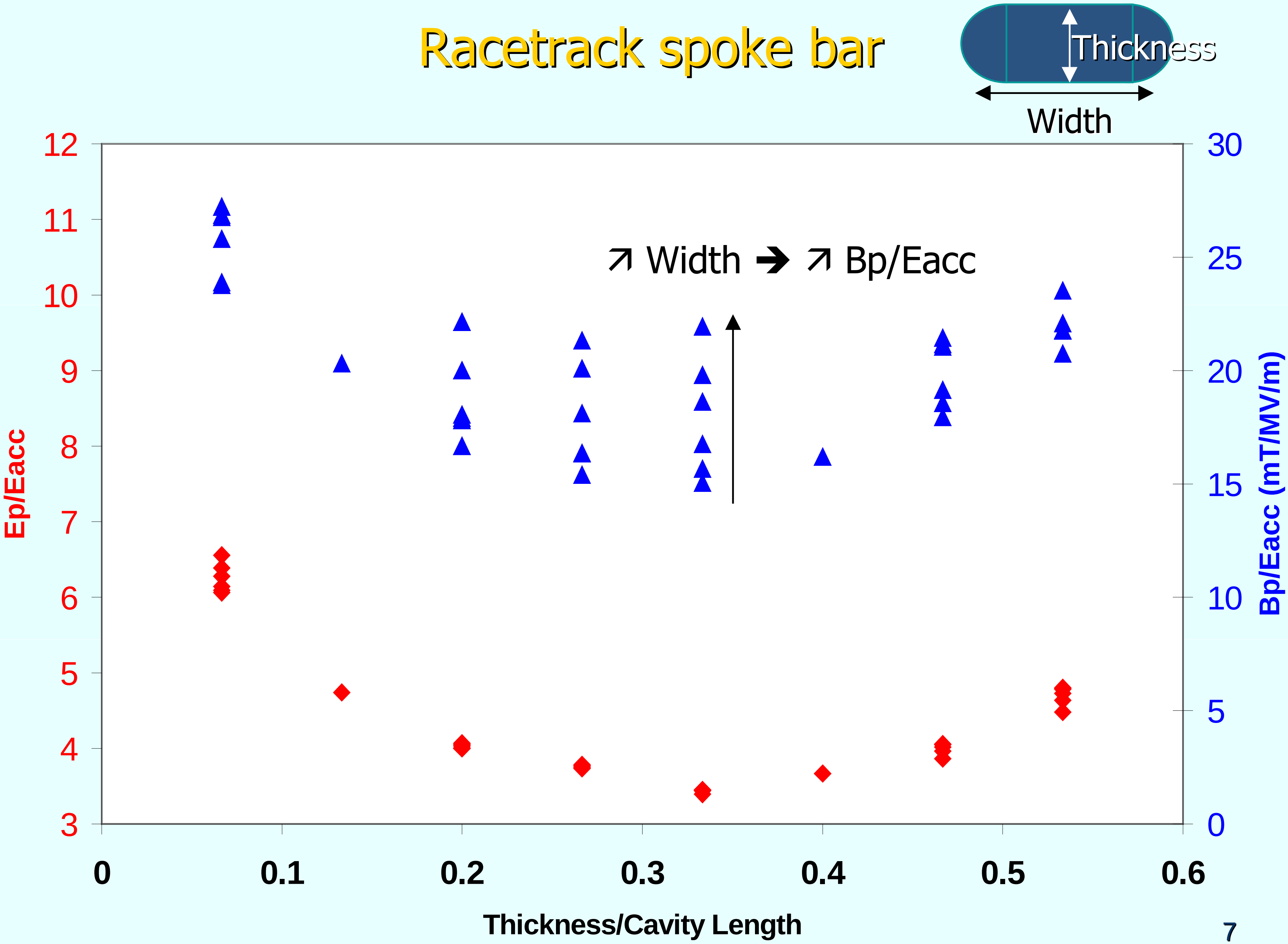
	Ep/Eacc	Bp/Eacc (mT/MV/m)
	3.60	13.8
	3.40	15.5
	3.40	15.0

Minimum for $D/L_{cav}=1/3$

Elliptical spoke bar



Racetrack spoke bar



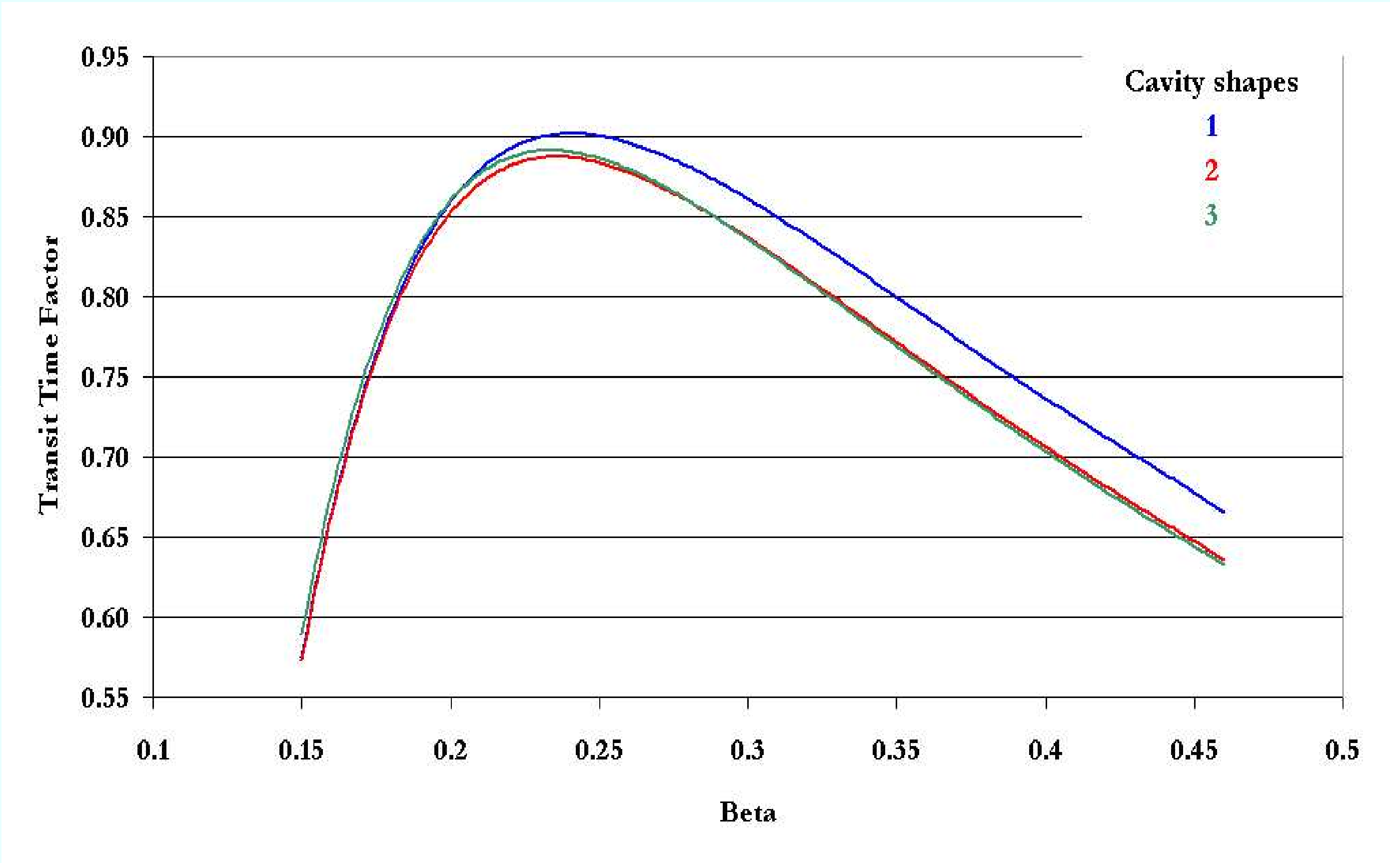
RF design

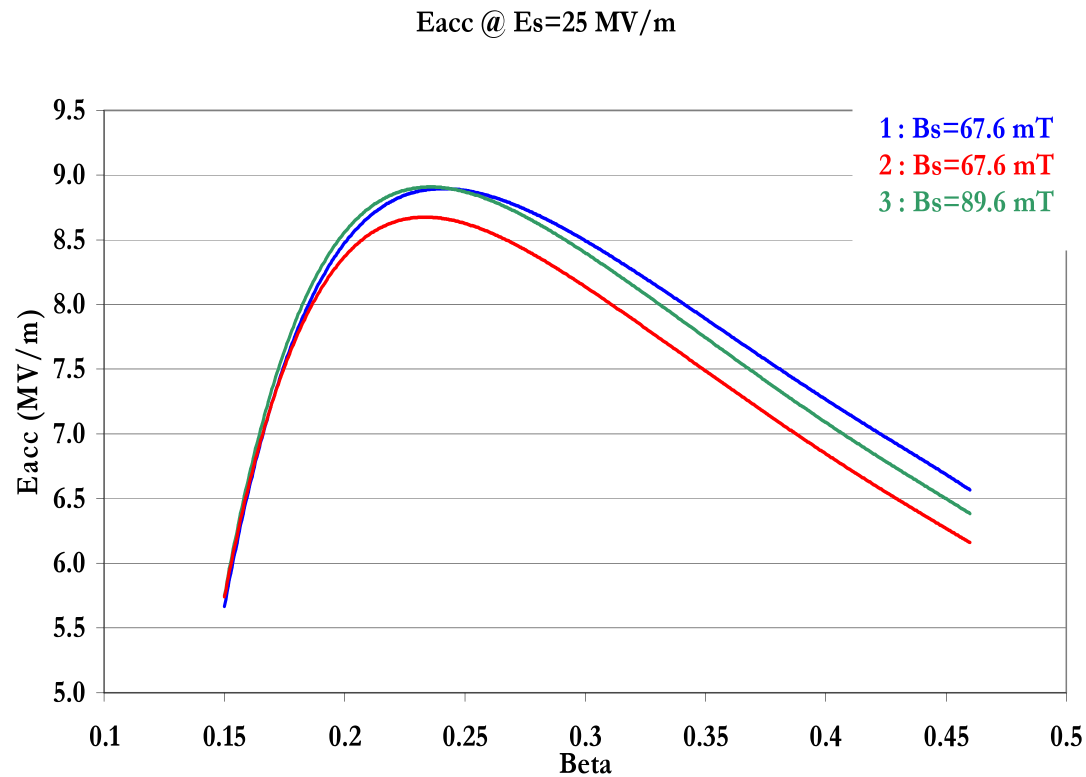
Comparison : 3 types of cavity (f=320 MHz, β_g0.24)

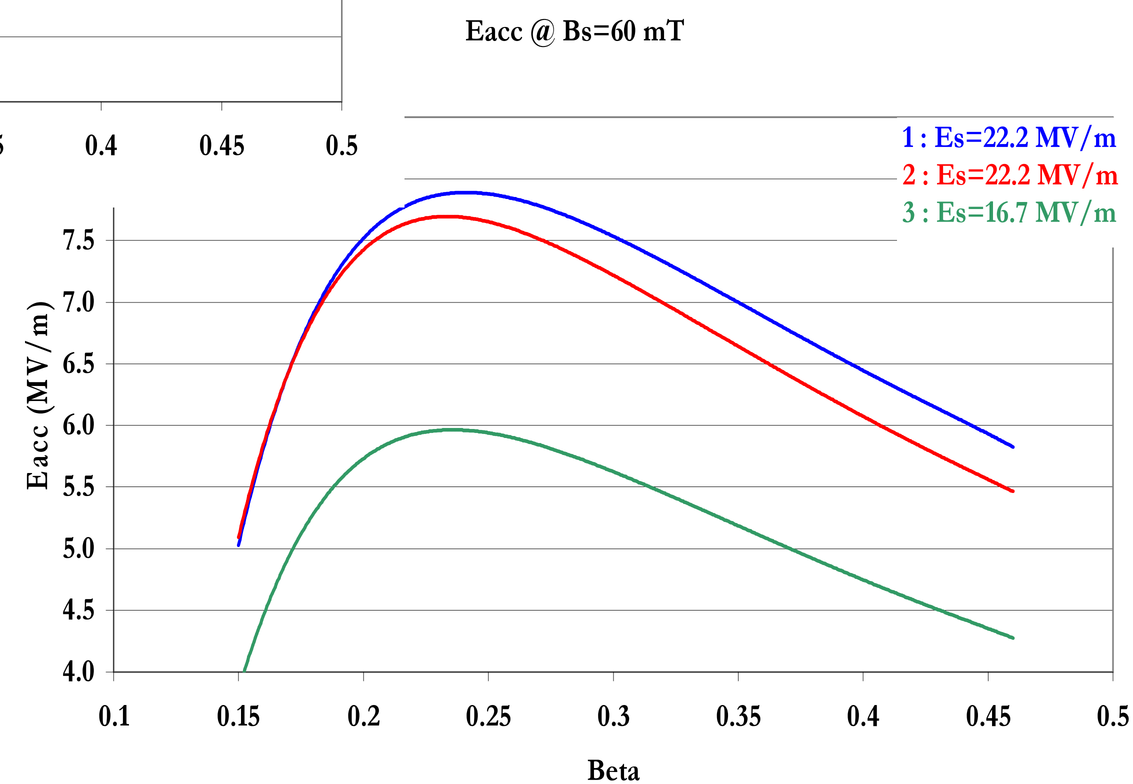
1 Cylindrical spoke base + racetrack spoke center & reentrant end walls

2 Cylindrical spoke bar & reentrant end walls

3 Pillbox with cylindrical spoke bar




Eacc @ Es=25 MV/m
1 : Bs=67.6 mT
2 : Bs=67.6 mT
3 : Bs=89.6 mT
Eacc (MV/m)
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Beta


Eacc @ Bs=60 mT
1 : Es=22.2 MV/m
2 : Es=22.2 MV/m
3 : Es=16.7 MV/m
Eacc (MV/m)
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Beta

Conclusion

Best design

Cylindrical spoke base + racetrack spoke center & reentrant end walls

RF parameters

Frequency (MHz)	358.66
Rs @ 4K (nΩ)	53
r/Q (Ω)	220
G (Ω)	101
Es/Eacc	3.06
Bs/Eacc (mT/MV/m)	8.28
Eacc @ Es=25 MV/m (MV/m)	8.18
Voltage gain (MV)	1.64
Optimum beta	0.36

Residual resistance=10 nΩ

Lacc=200 mm

Discussion on "XADS/Eurisol" by Guillaume Olry

Olry was asked about the strategy when optimizing spoke shapes. He clarified that while the spoke of the resonator built was varying (circular base and race-track at the aperture), the optimization curves that compared circular vs. elliptical vs. racetrack spokes were for homogeneous spoke cross-sections.

The nominal thickness of the spokes was 1/3 of the total active length of the cavity. Delayen and Shepard pointed out that this is contradictory to their findings that peak fields are lowest, if the spoke is approximately ? of the total active cavity length. The reason might be that spoke variations for each spoke type did not take into account the change in the structure β, defined by the gap-center to gap-center distance that varied during the optimization.

Olry was asked about the reason for a 359 MHz resonant frequency of their cavity. He explained that the target frequency had been 352 MHz. Due to an error in the racetrack specification the frequency came in higher, which was not an issue to demonstrate this prototype resonator.

SC RF Cavity Activities at FZJ

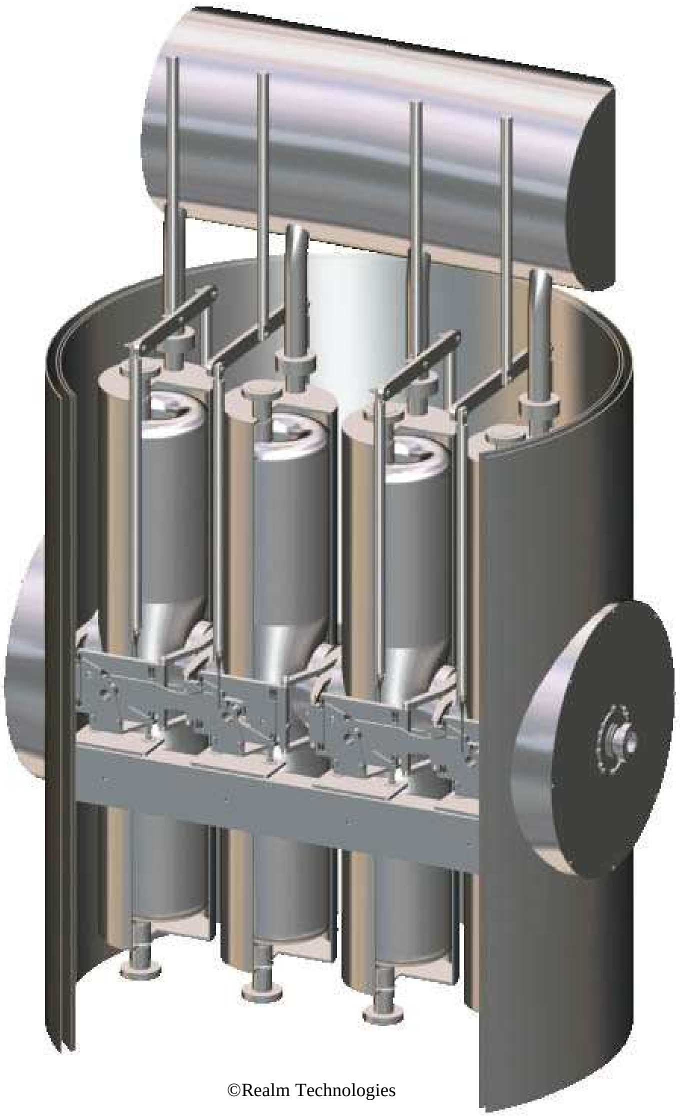
E. Zaplatin, W. Braeutigam, M. Pap, U. Rindfleisch, M. Skrobucha, R. Stassen, Forschungszentrum Juelich

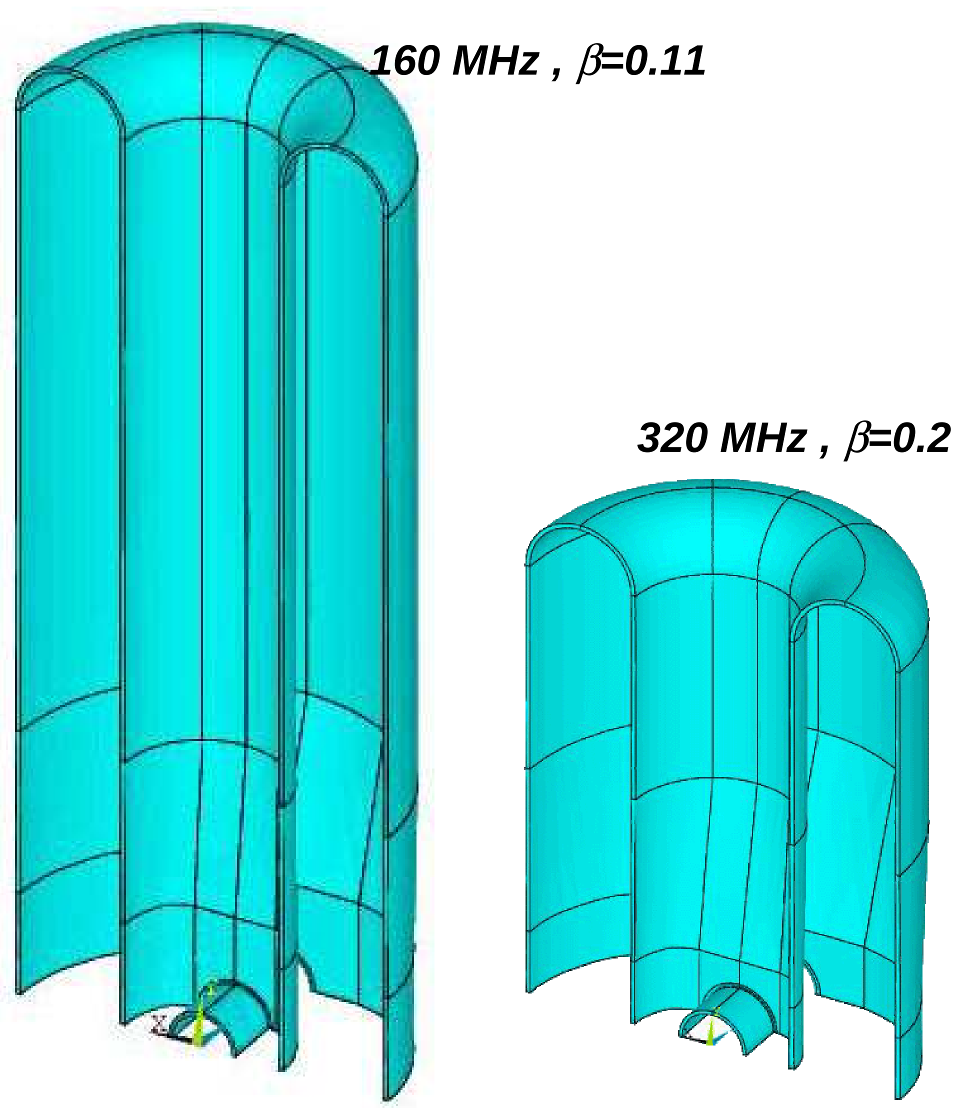
We report the status of work going on in Forschungszentrum Juelich on SC RF cavity investigations – five-cell elliptic cavity (500 MHz, beta=0.75), low-beta half-wave length cavities for new COSY Injector (160 MHz, beta=0.11 and 320 MHz, beta=0.2) and multigap spoke cavity as a possible accelerating structure for low energy part of ESS (700 MHz, beta=0.2).

SC RF CAVITY ACTIVITTIES @ FZJ

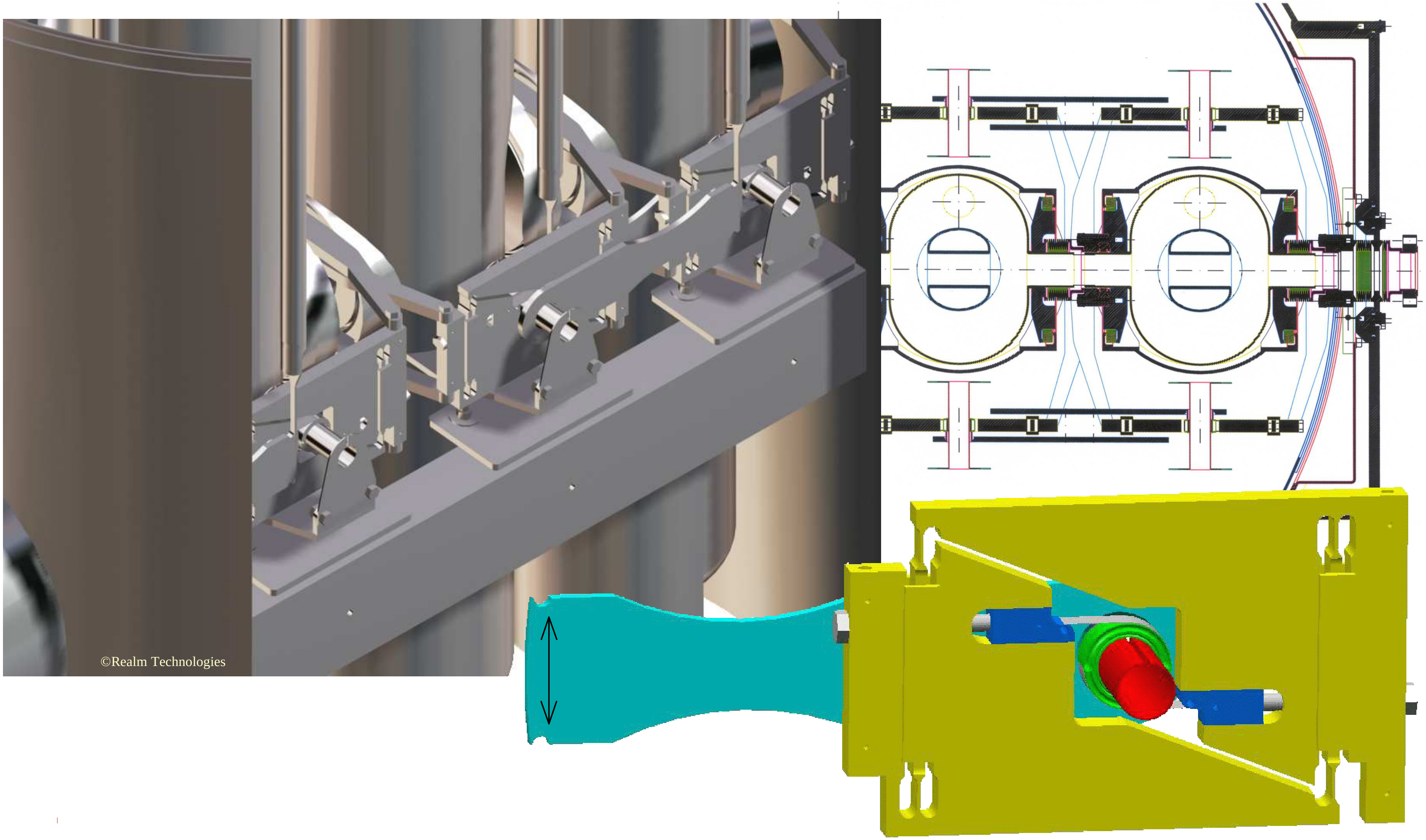
E. Zaplatin, W. Bräutigam, M. Pap, U. Rindfleisch, M. Skrobucha, R. Stassen

COSY SC LINAC CAVITY GEOMETRY



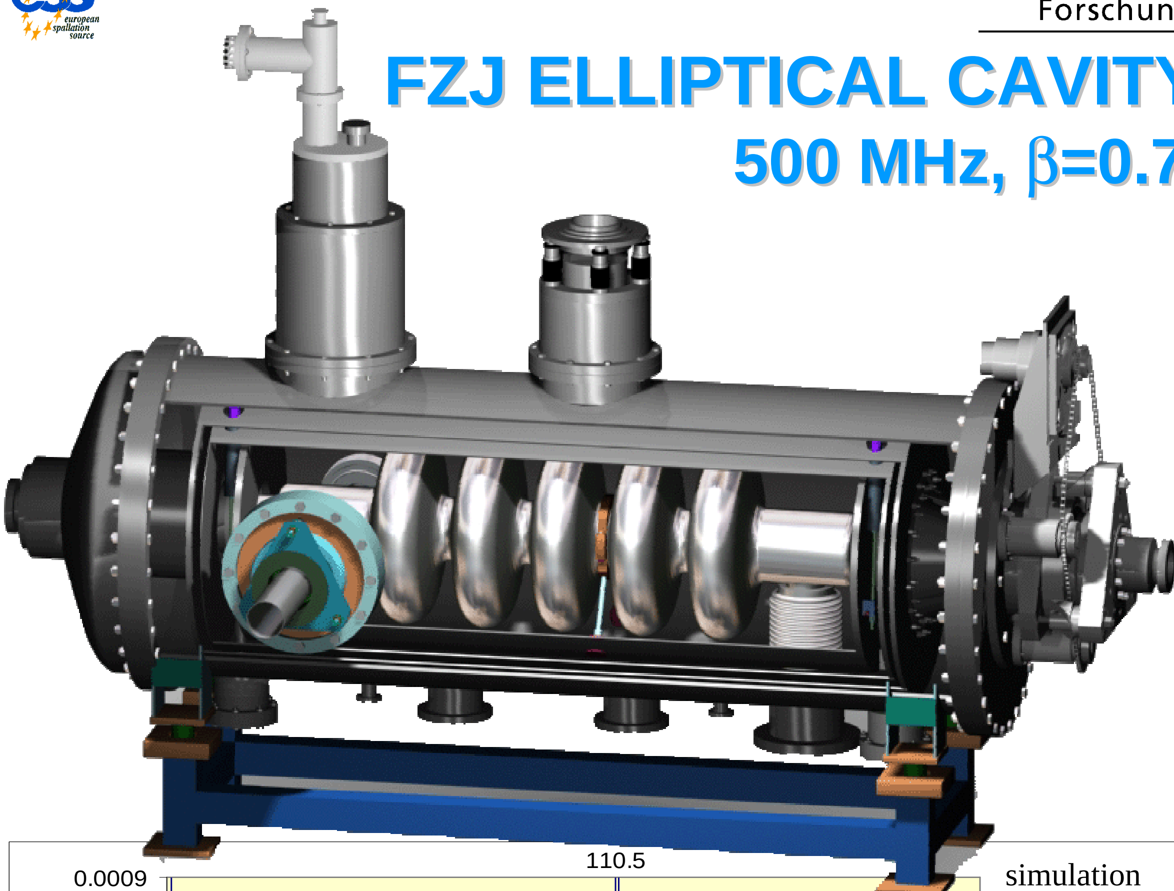


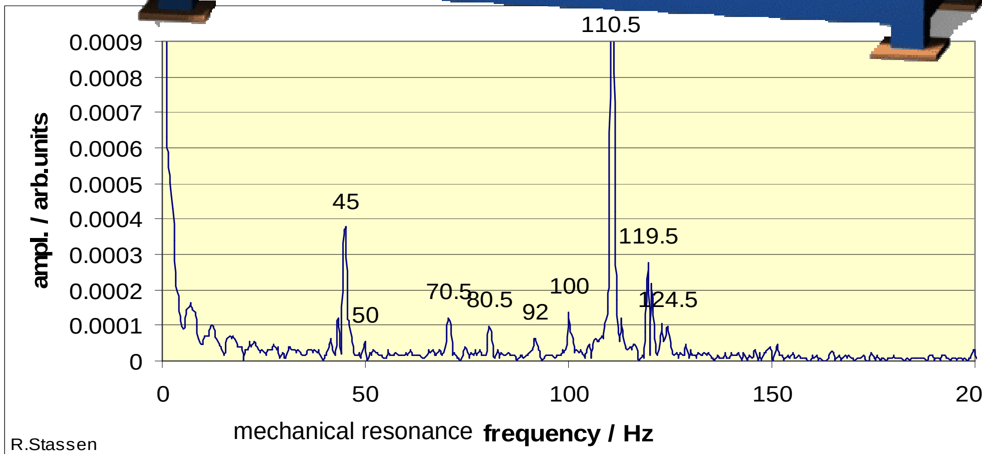
COSY SC LINAC CAVITY TUNER



FZJ ELLIPTICAL CAVITY ANALISYS

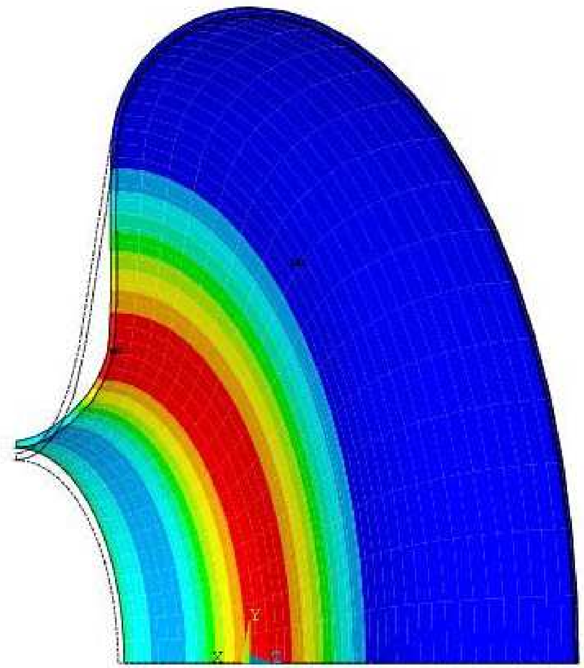
500 MHz, β=0.75





simulation results

mode	frequency / Hz
1	46.887
2	67.522
3	68.555
4	110.77
5	131.90
6	157.97
7	181.12
8	191.03



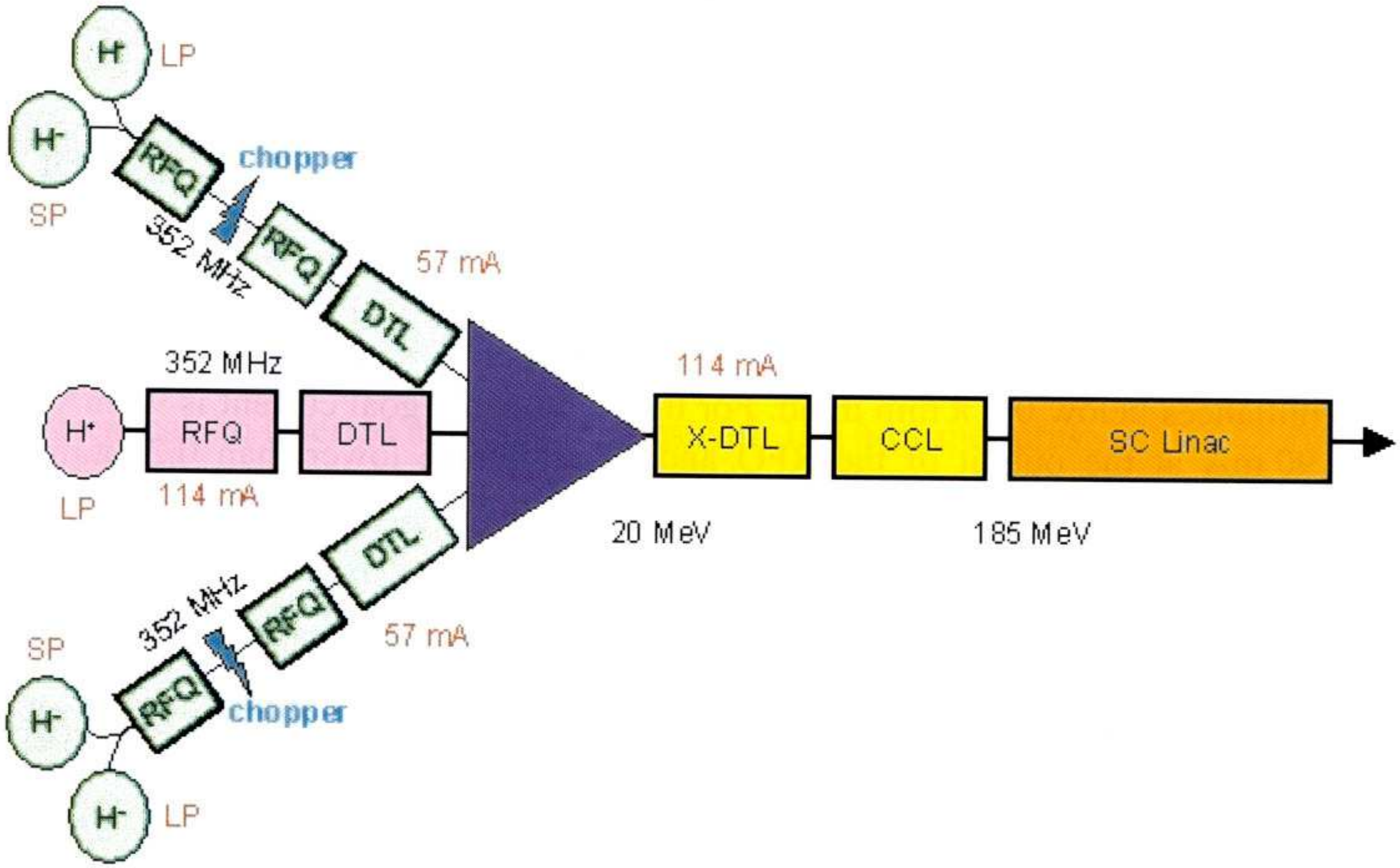
LFD

max displ. 0.00011 mm

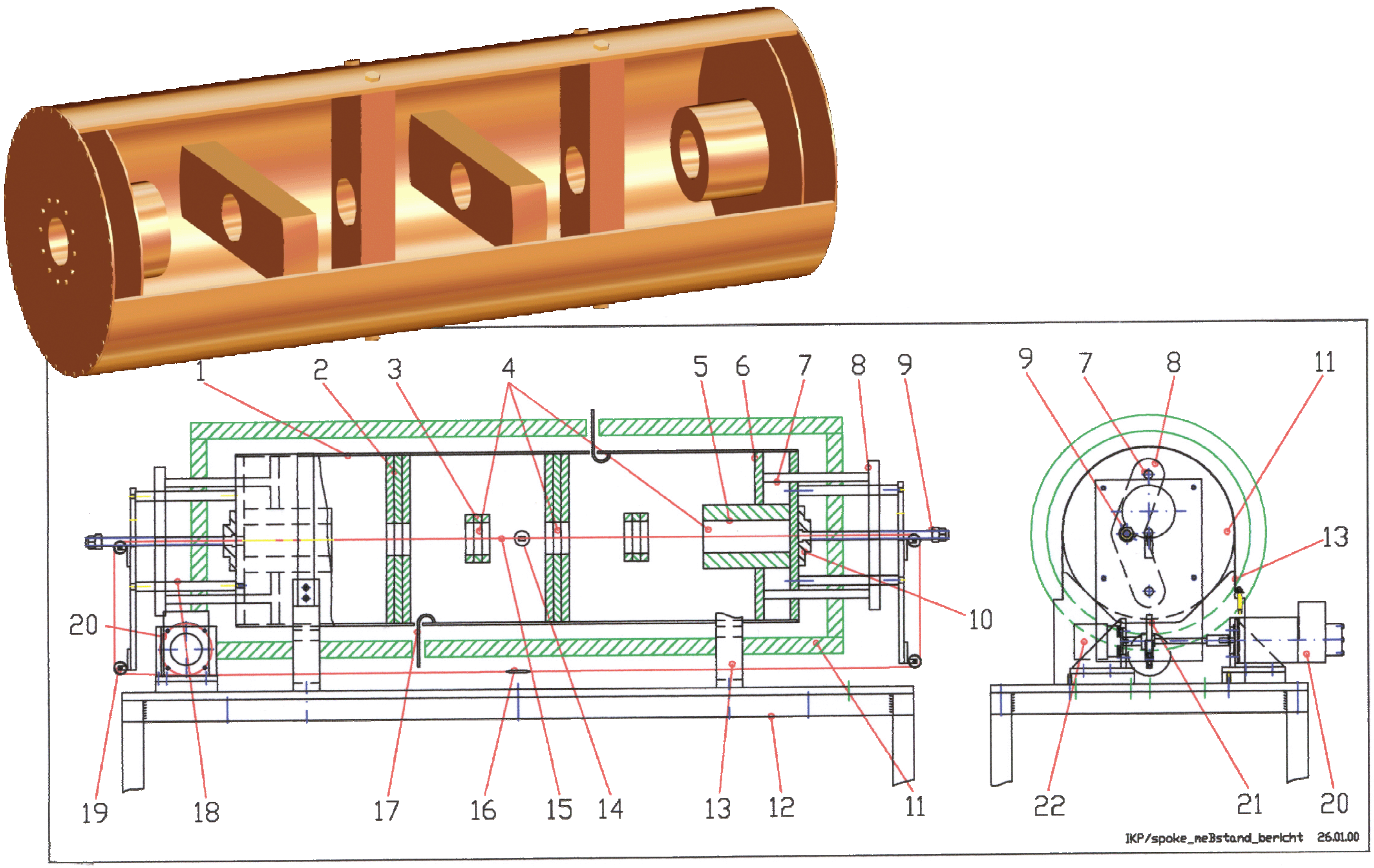
$$k_{calc} = -3.95\ Hz/(MV/m)^2$$

$$k_{exp} = -3.72\ Hz/(MV/m)^2$$

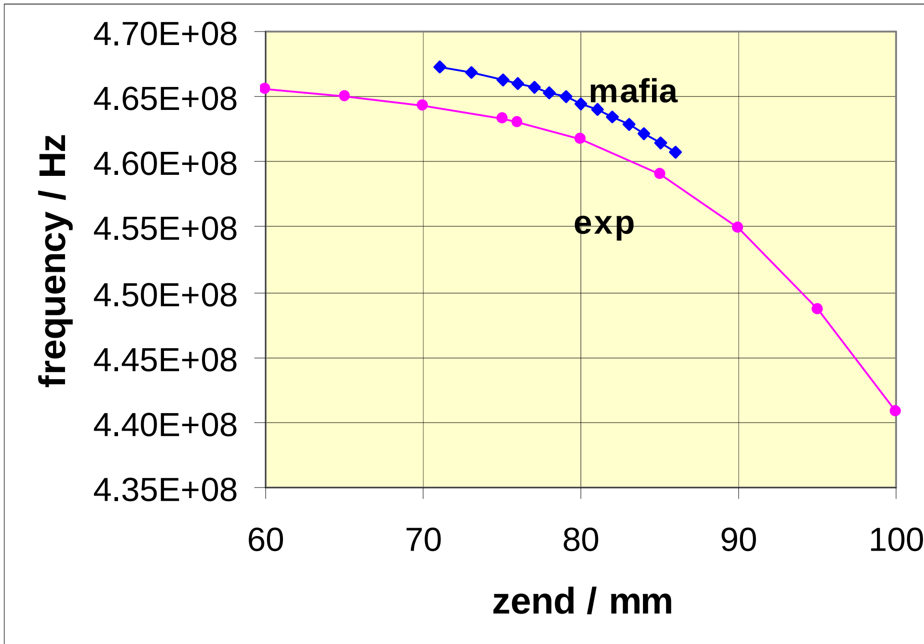
ESS 352/704 MHz SC Scheme

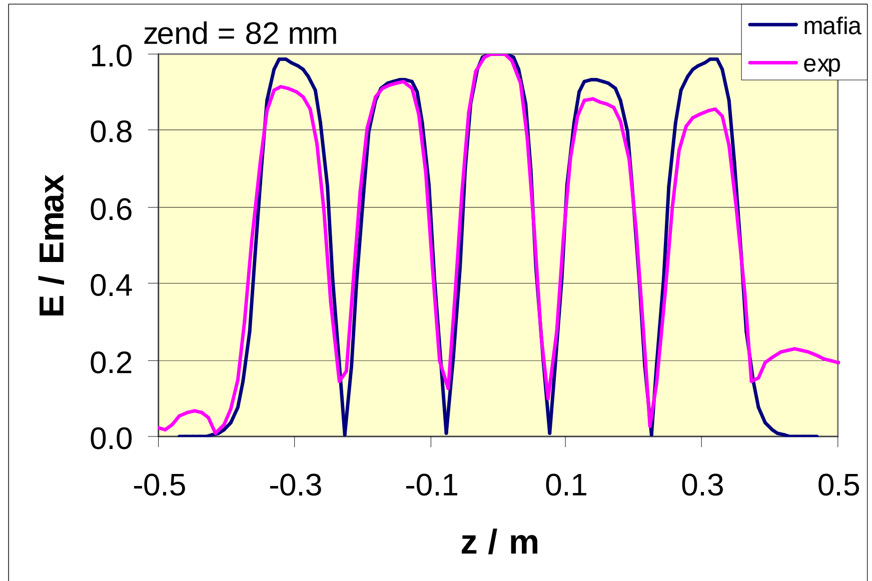


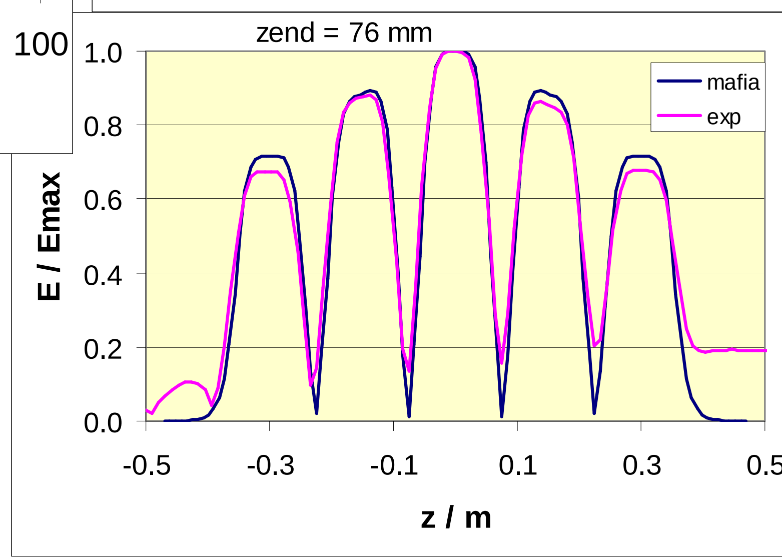
5-GAP H-CAVITY MODEL (500 MHz , β=0.5)



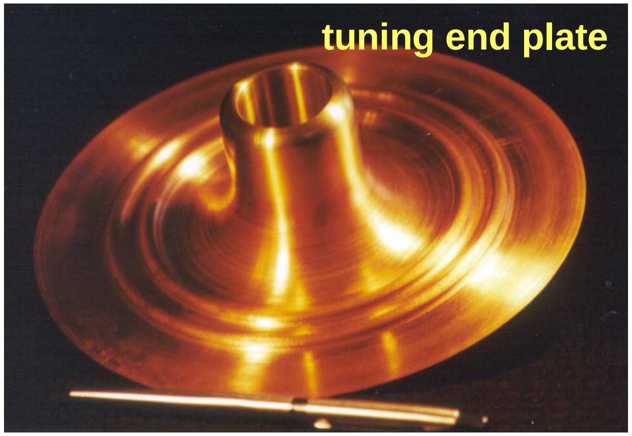
5-GAP H-CAVITY MODEL (500 MHz , β=0.5)

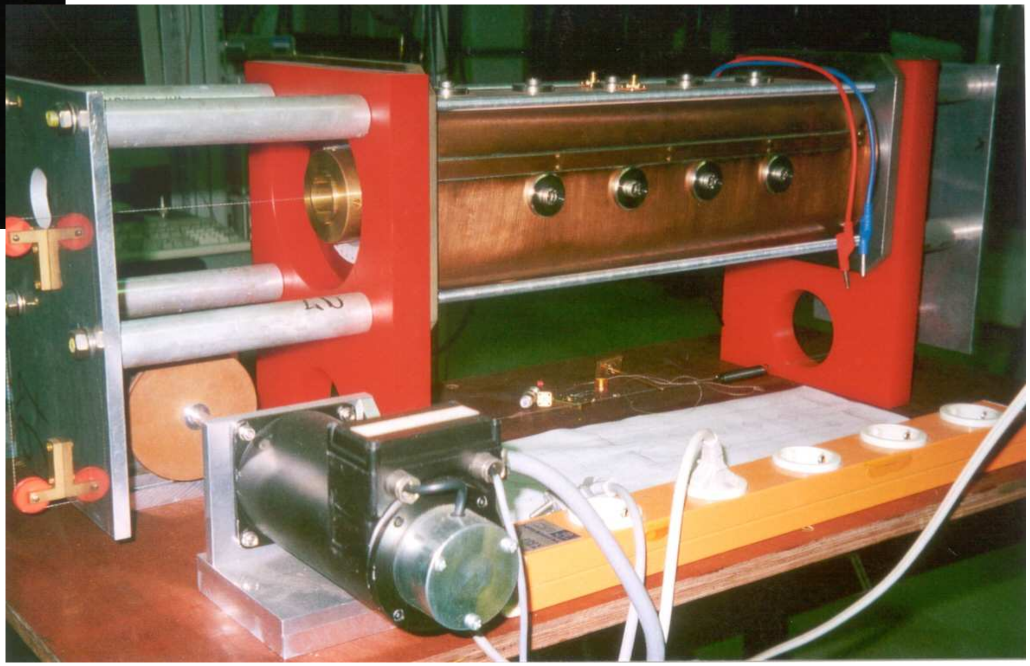






10-Gap SCH-Cavity Copper Model (700 MHz , β = 0.2)





RF Measurement Goals:

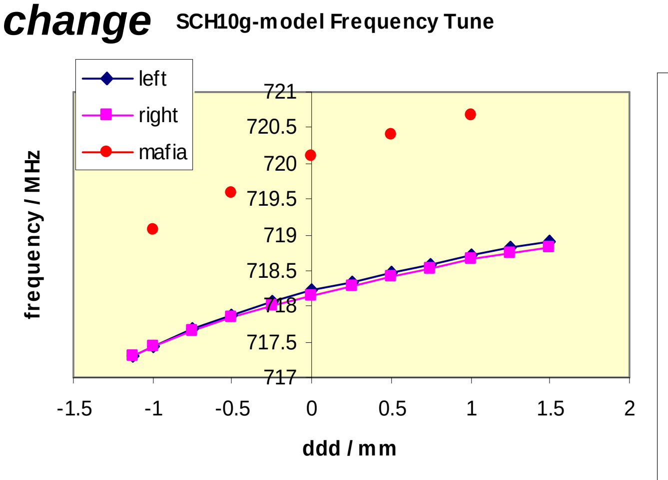
1. 3D Simulation Verification

2. Cavity Tuning Investigation

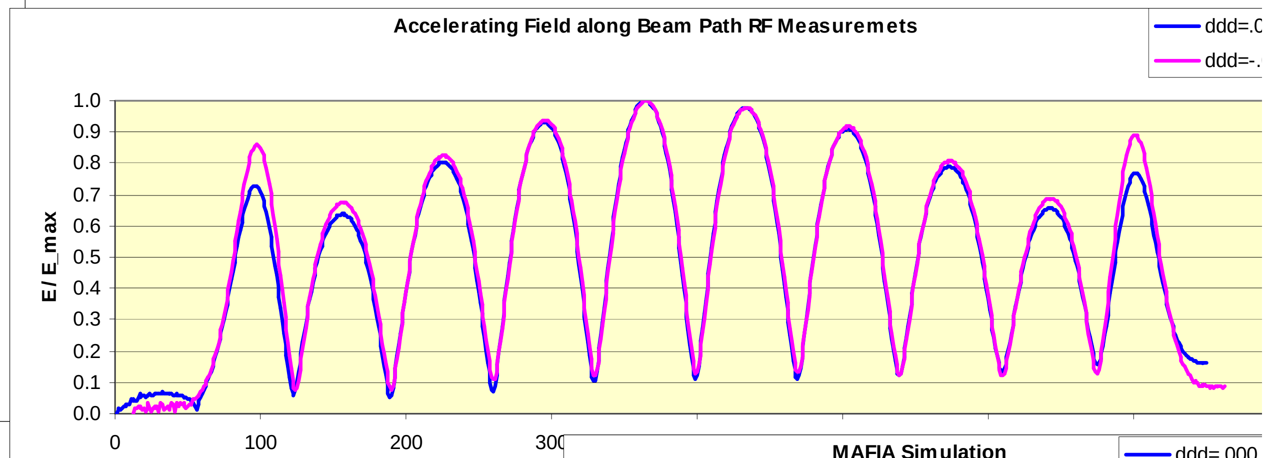
Forschungszentrum Jülich

10-Gap SCH-Cavity Copper Model (700 MHz , β = 0.2)

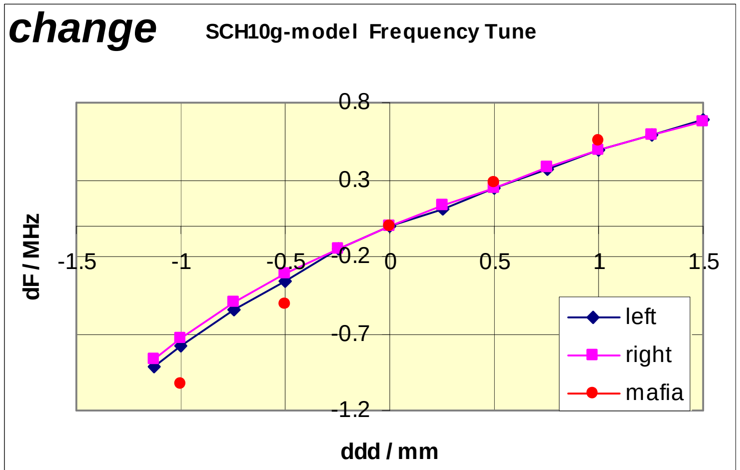
Frequency vs. last acc. gap change

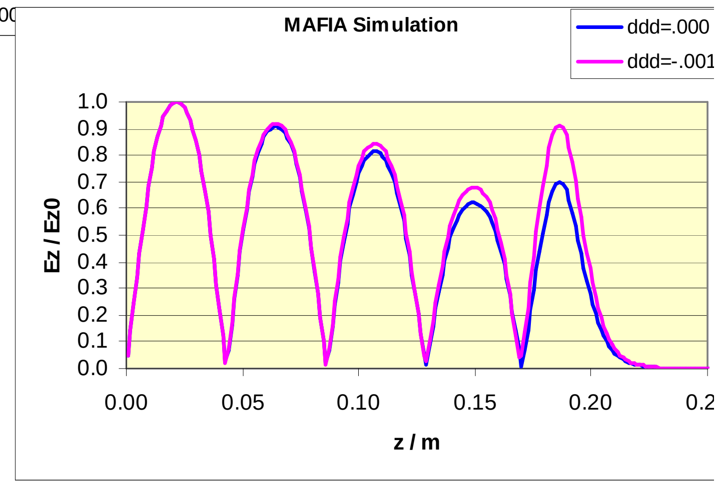


Acc. Field along Beam Path RF Measurements

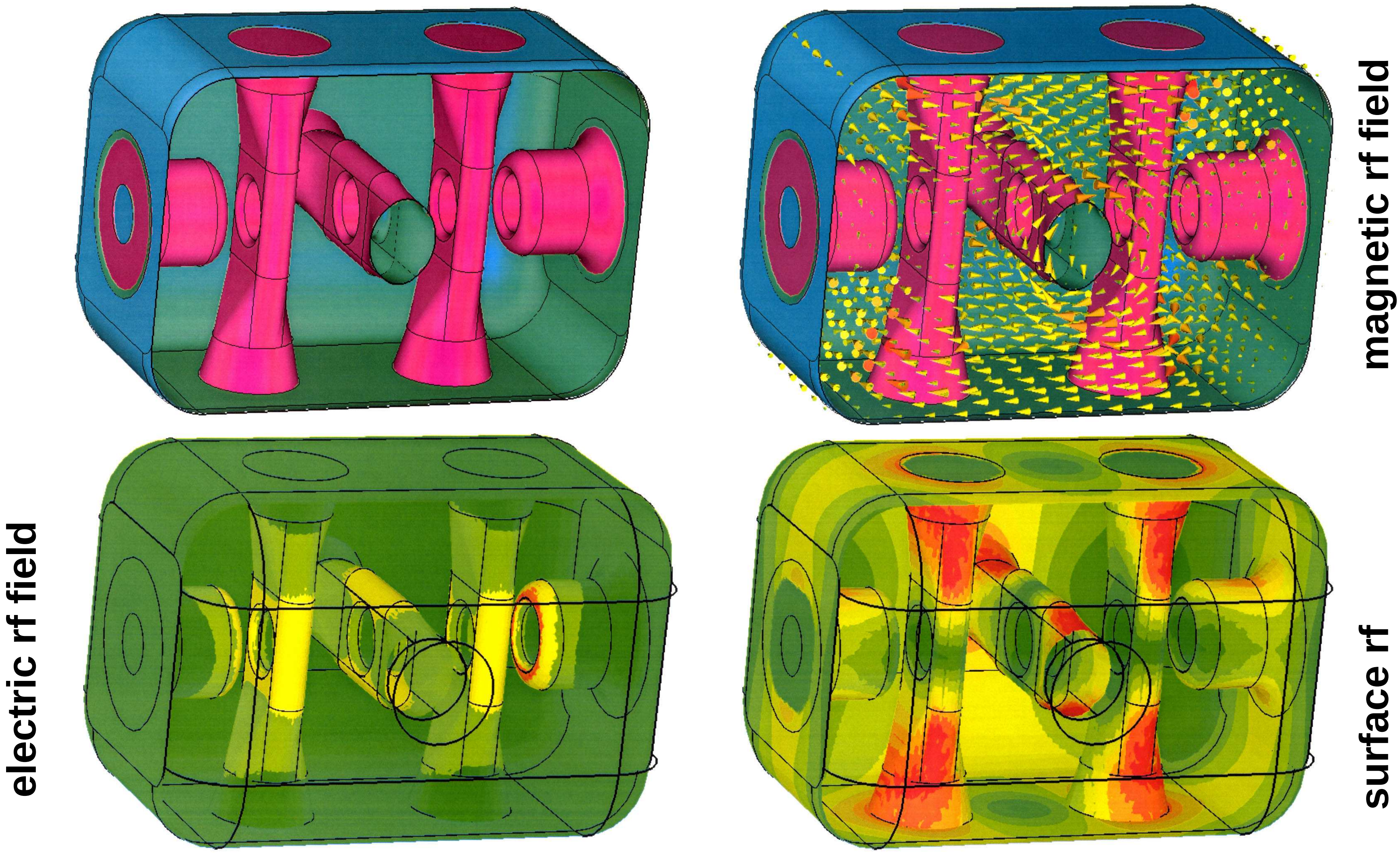


Frequency shift vs. last acc. gap change



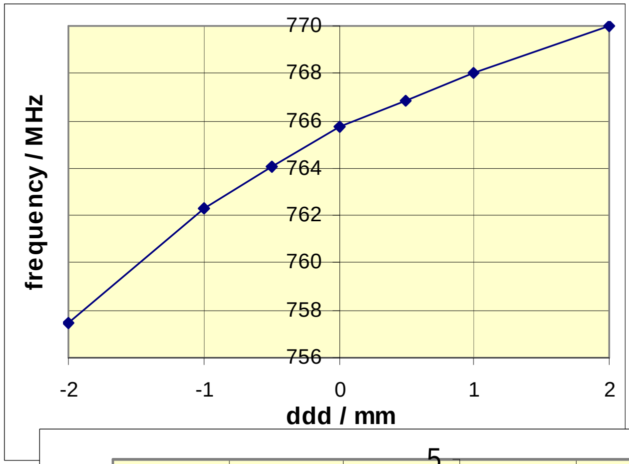


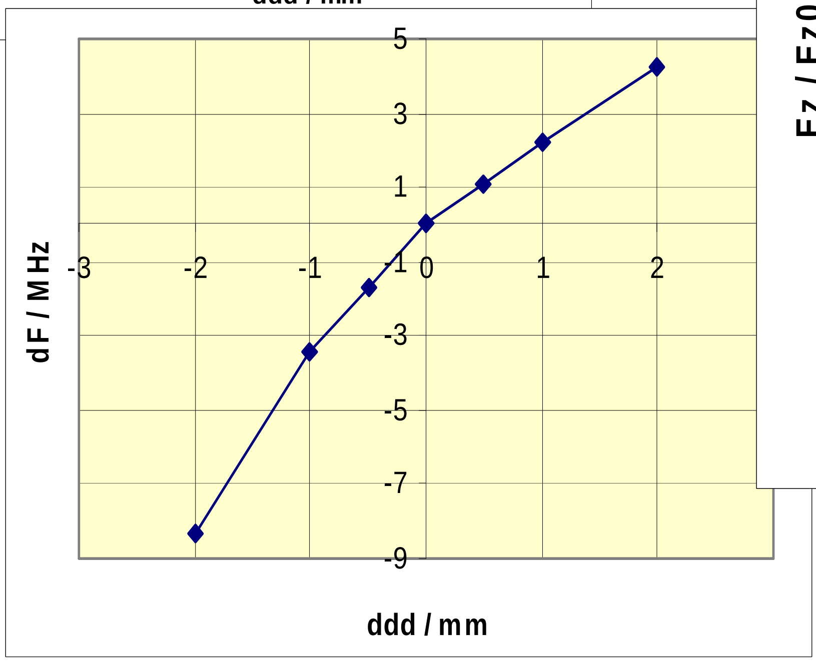
SC 4-GAP H-CAVITY (700 MHz , β=0.2)

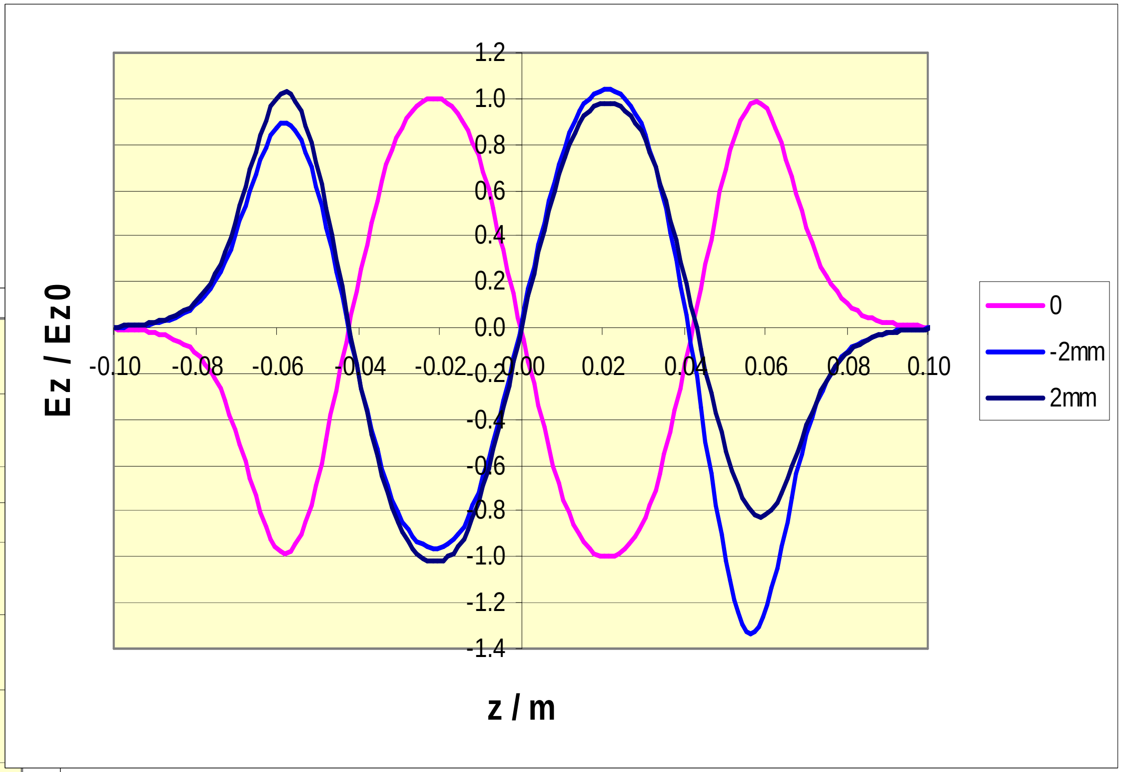


SC 4-GAP H-CAVITY (700 MHz , β=0.2)

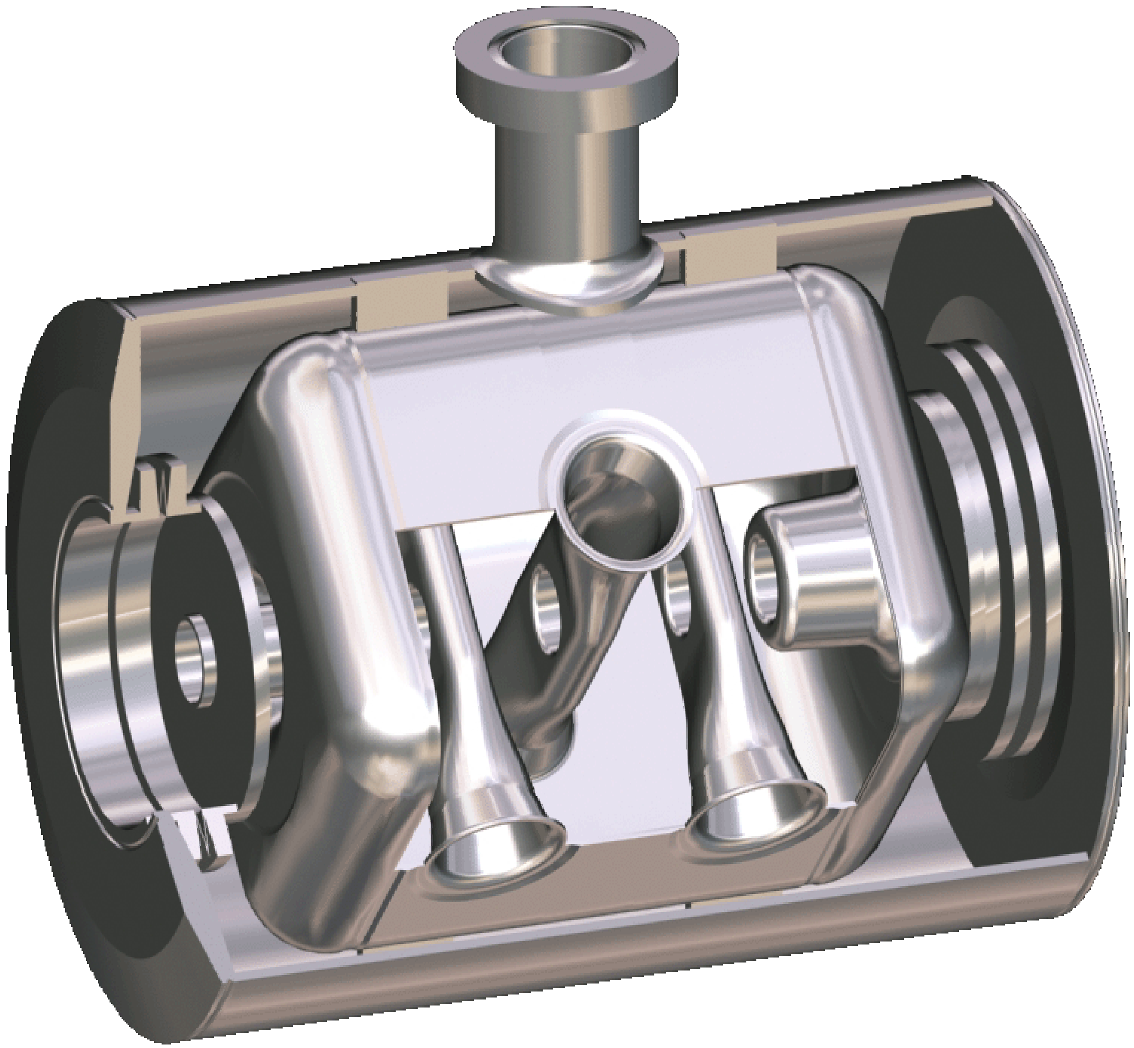
cavity tune



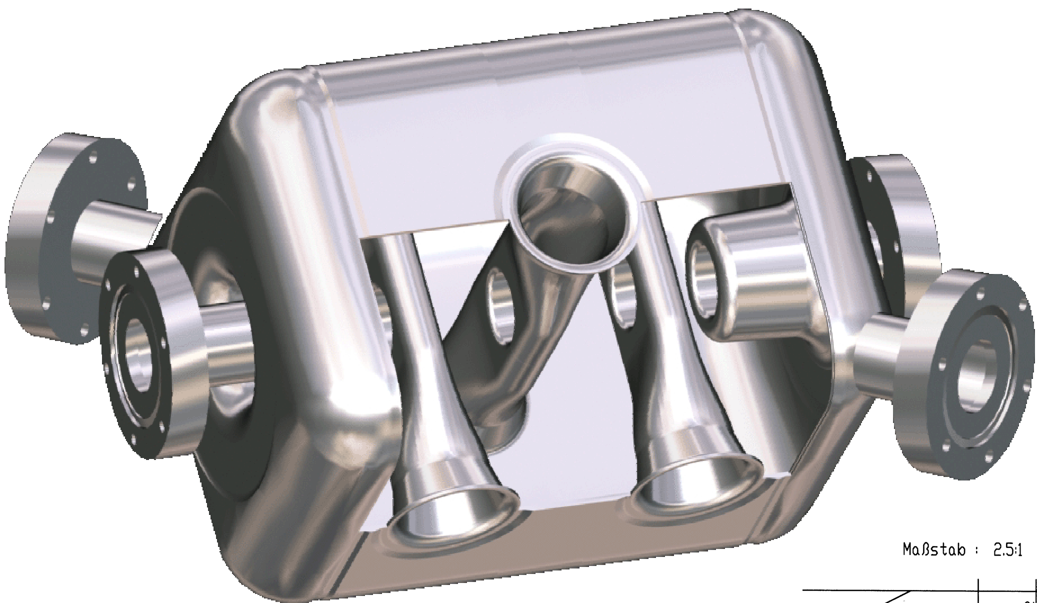


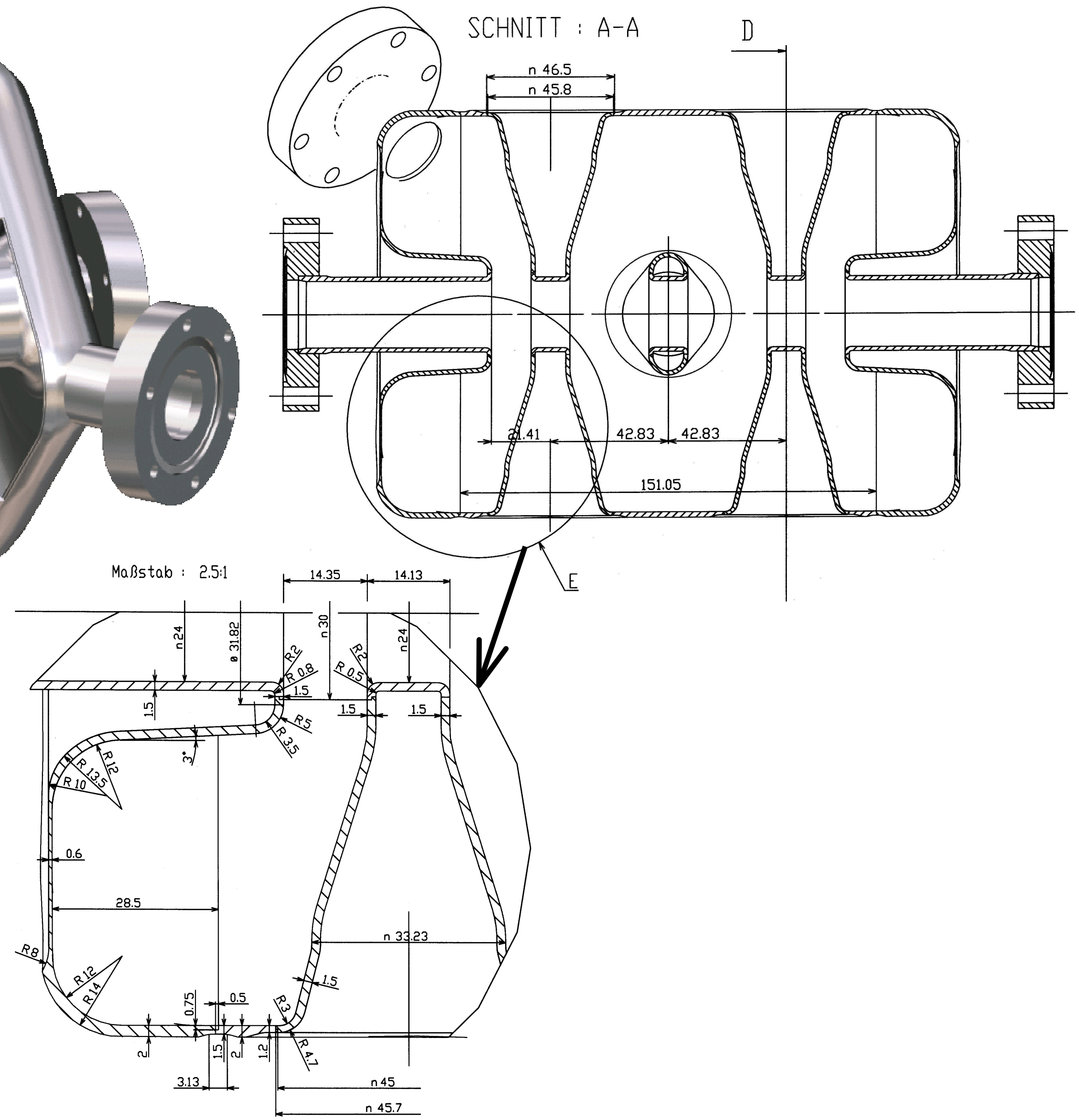


SC 4-GAP H-CAVITY IN CRYOMODULE
(700 MHz , β=0.2)



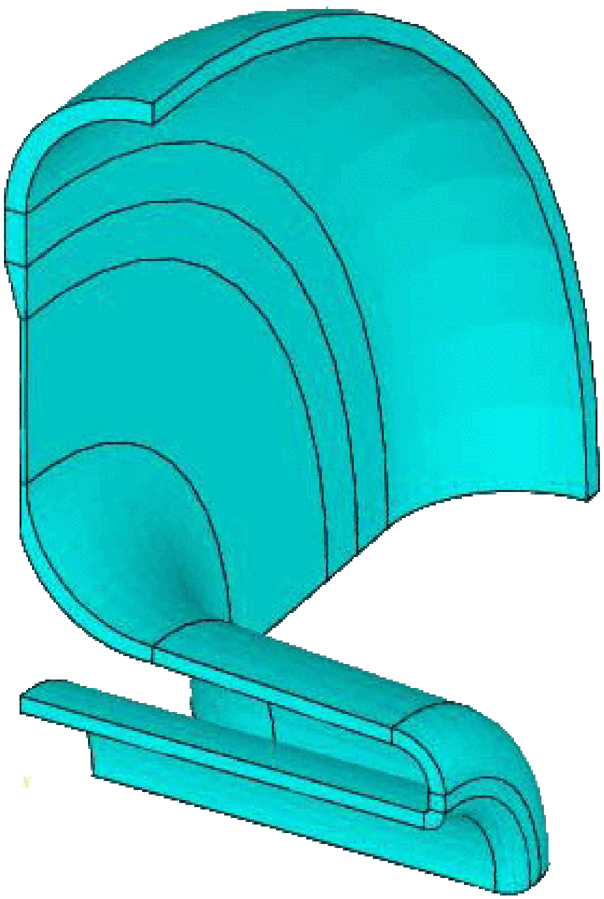
SC 4-GAP H-CAVITY (700 MHz , β=0.2)

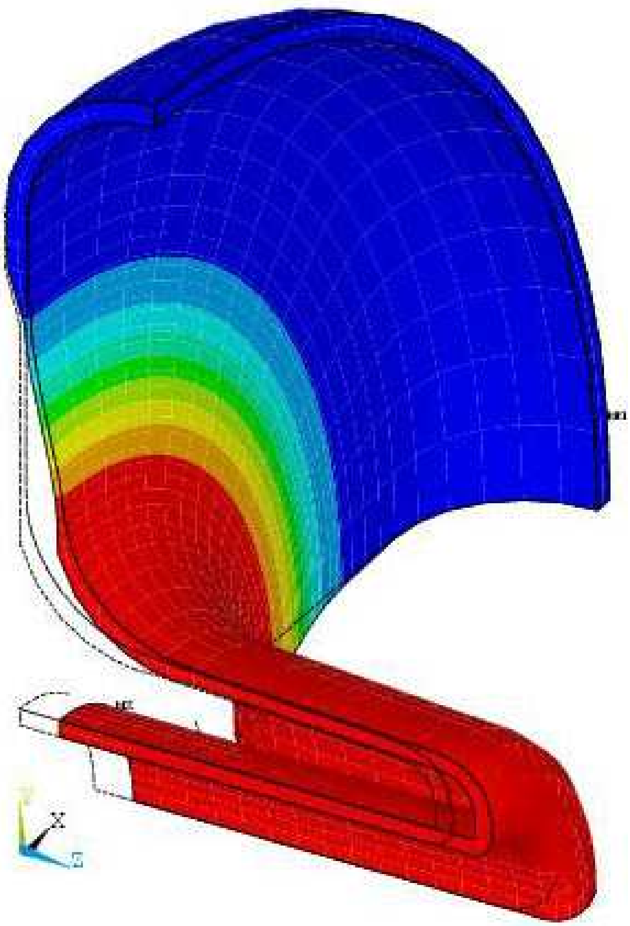




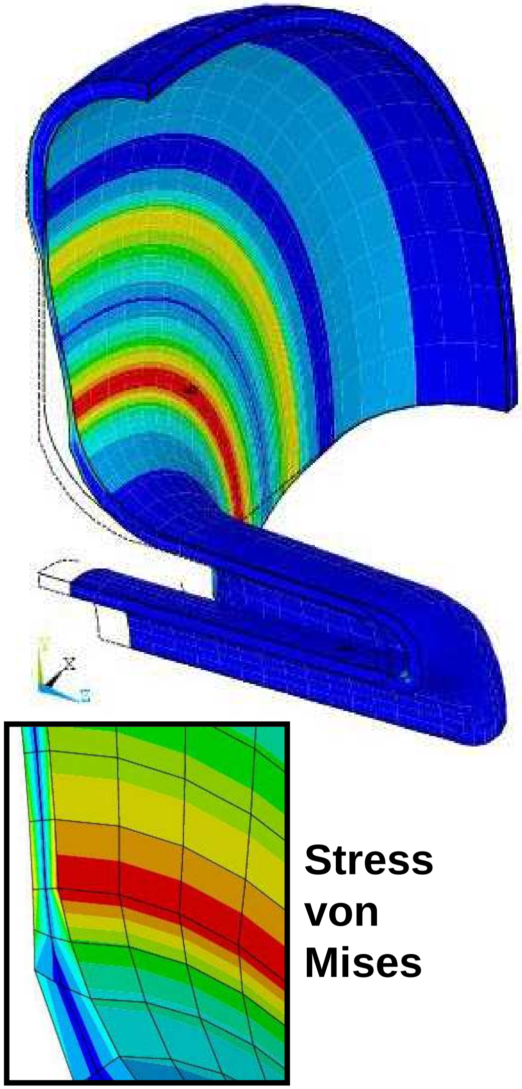
Frequency	MHz	775
β=v/c		0.2
R aperture	cm	1.5
$\beta\lambda/2$	cm	4.283
R_{cav}	cm	7.15
E_{pk} / E_{acc}		4.93
B_{pk} / E_{acc}	mT/MV/m	8.17
B_{pk} / E_{pk}	mT/MV/m	1.66

TUNING PLATE
geometry



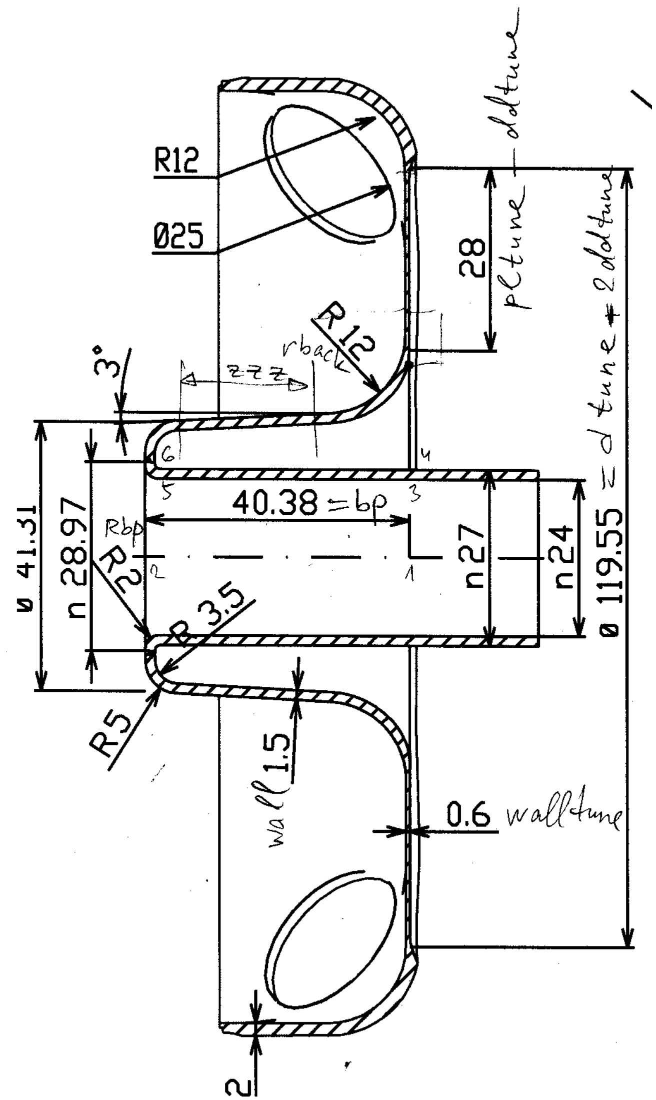


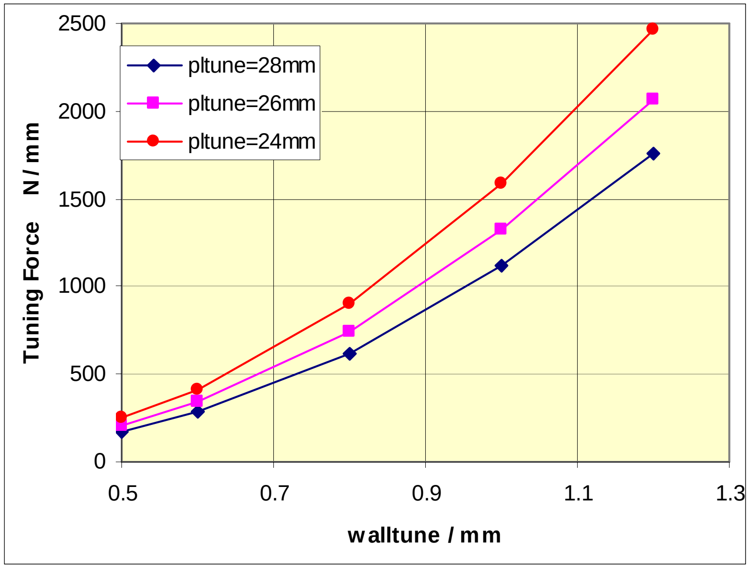
deformation by tuning

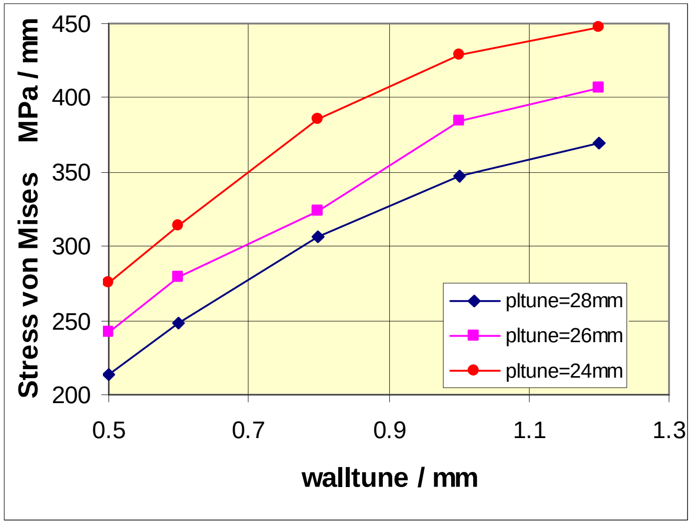


Stress von Mises

TUNING PLATE



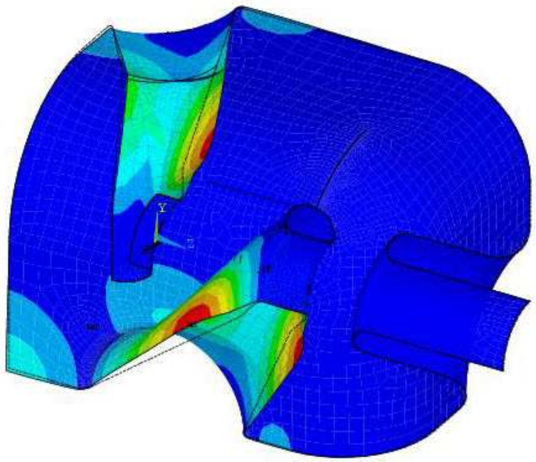


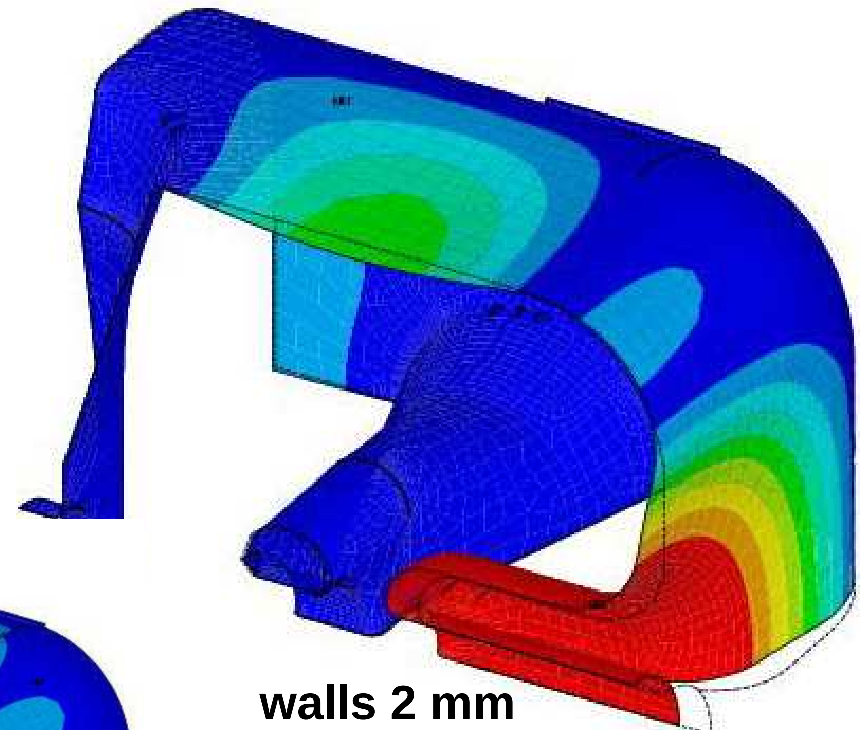


MECHANICS

LHe pressure 1 bar

Spokes (0.00475 mm)



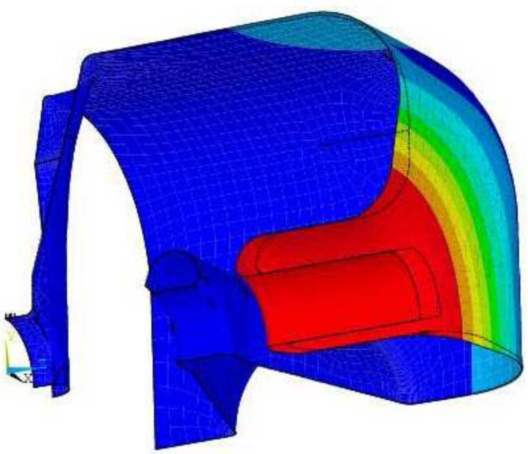


walls 2 mm

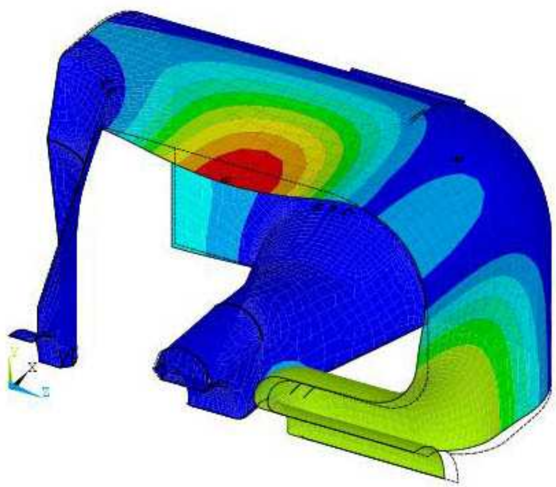
Spokes+Walls+End Electrode

max deformation 0.149 mm

frequency shift 494.2 kHz



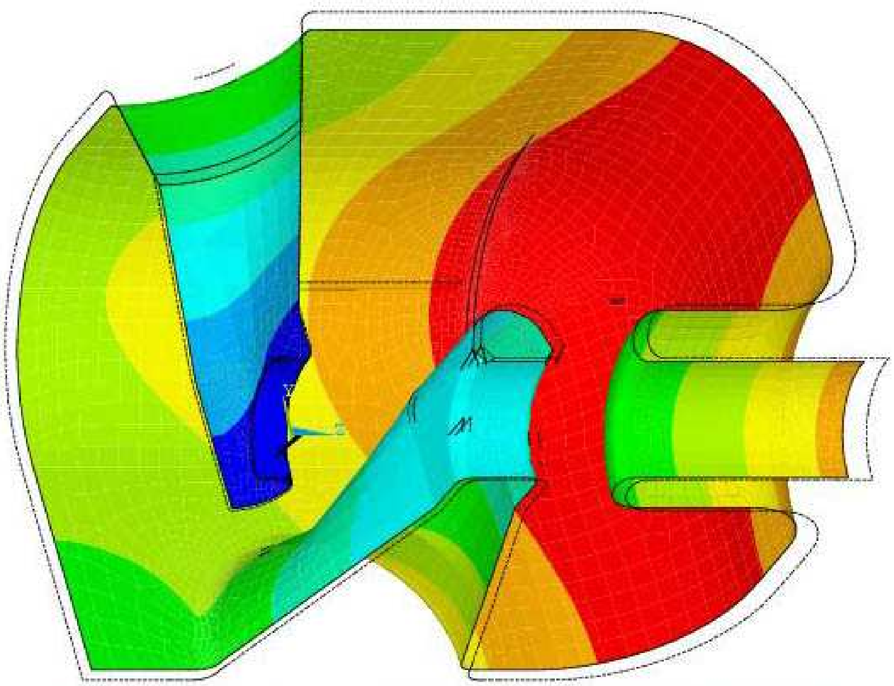
Spokes + End Electrode (0.0912 mm – 319 kHz)



Spokes + Walls (0.0875 mm – 26.8 kHz)

MECHANICS

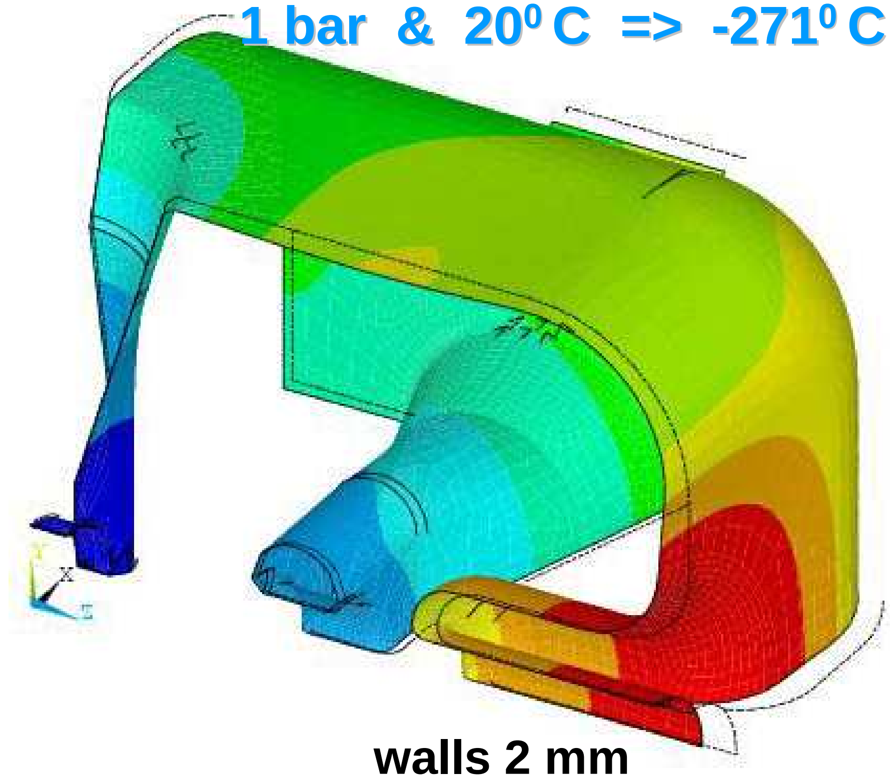
CAVITY COOL-DOWN
20^0 C => -271^0 C



walls 2 mm

max deformation 0.237 mm frequency shift 3.4 MHz

CAVITY COOL-DOWN + LHe PRESSURE
1 bar & 20^0 C => -271^0 C



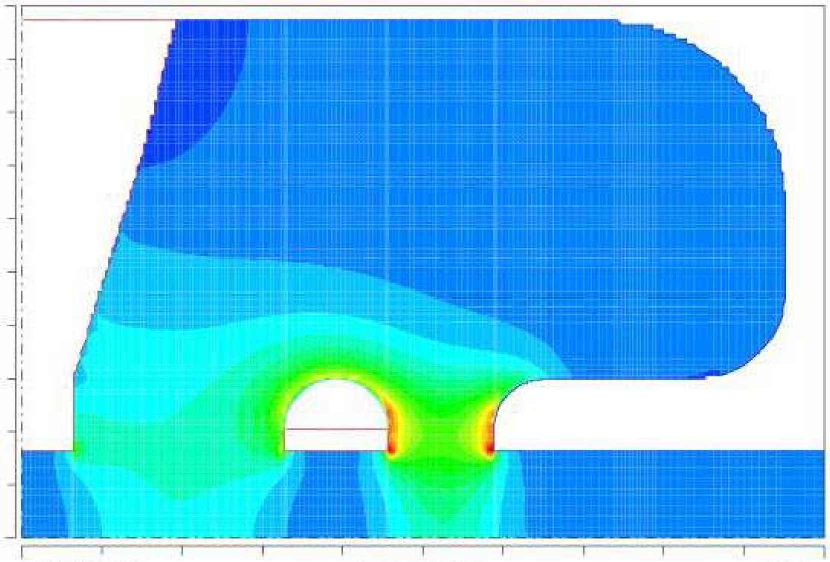
walls 2 mm

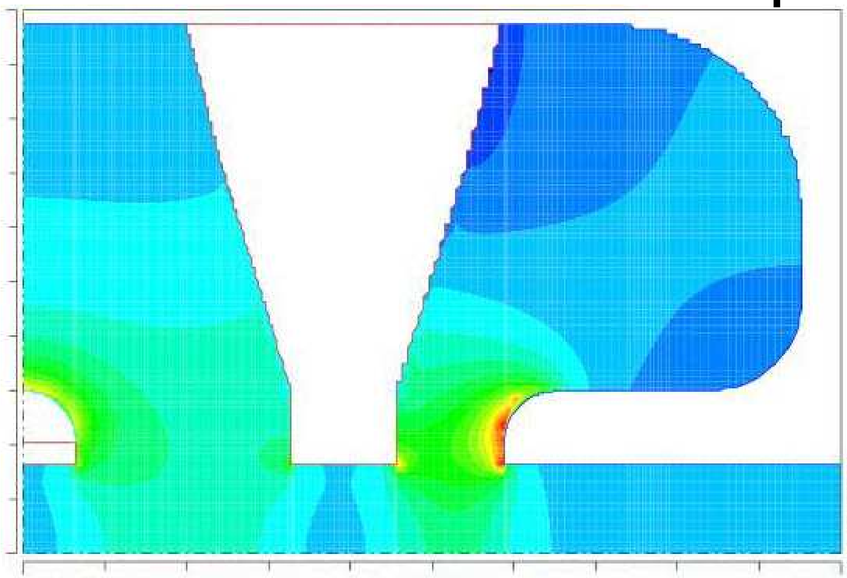
max deformation 0.361 mm frequency shift 3.88 MHz

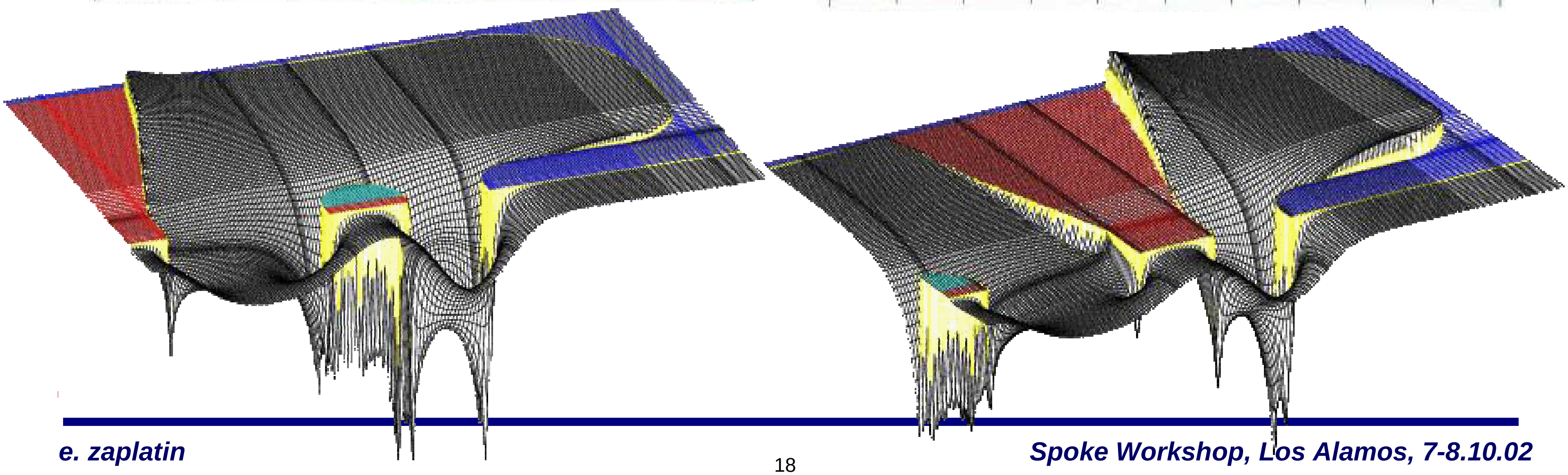
LORENZ FORCE PRESSURE

$$P=\mu_0 H^2-\varepsilon_0 E^2$$

X-plane **Y-plane**



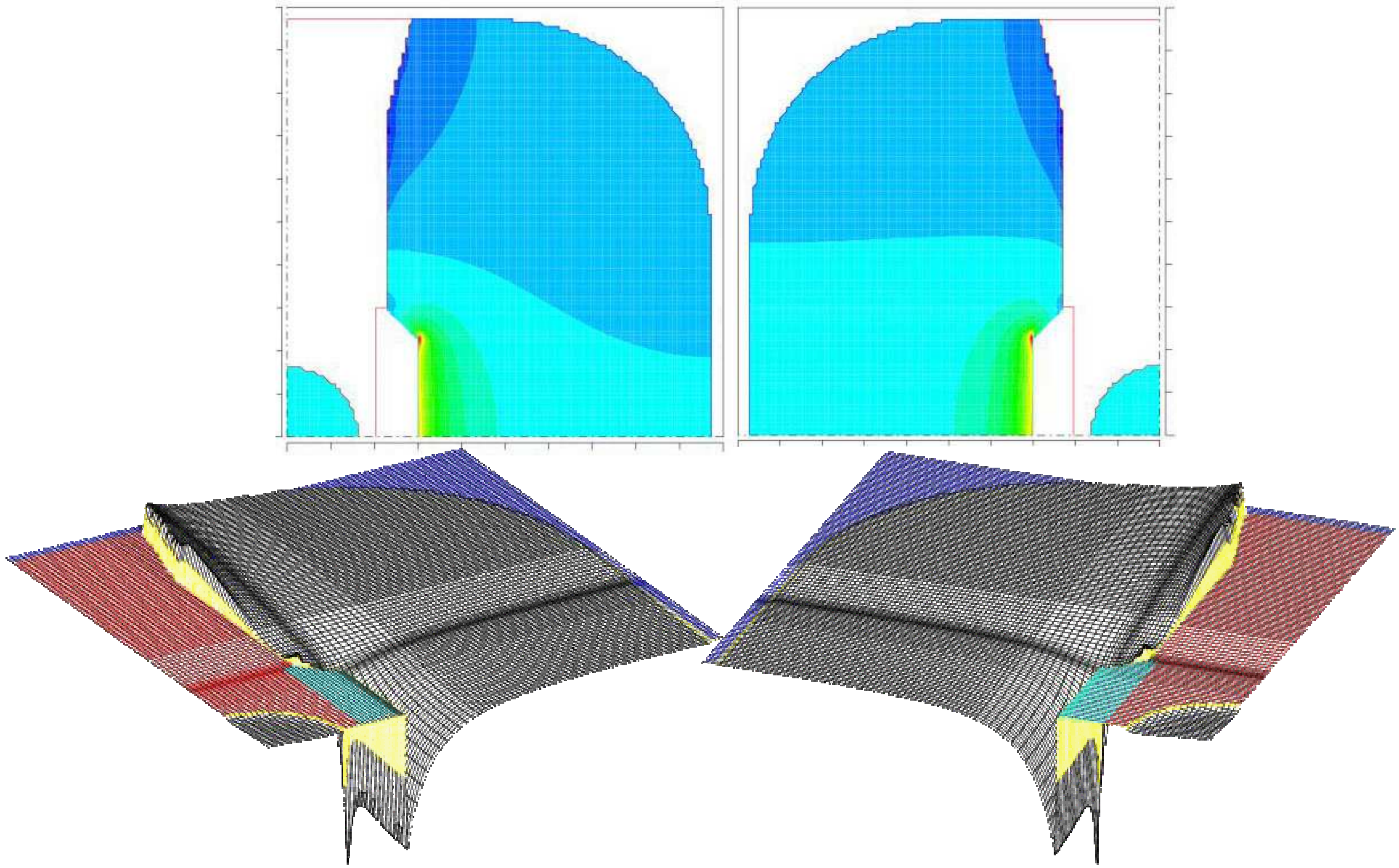




LORENZ FORCE PRESSURE

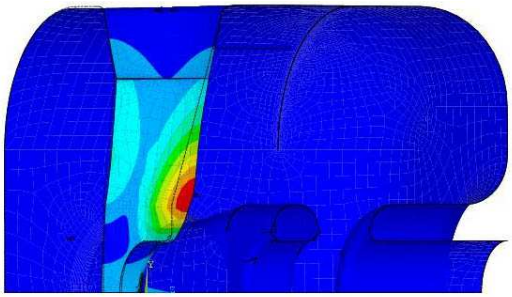
$$P=\mu_0 H^2-\varepsilon_0 E^2$$

mid-spoke **side-spoke**

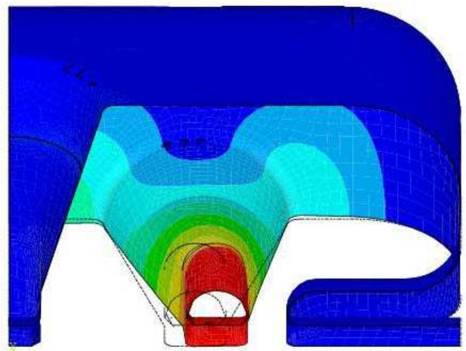


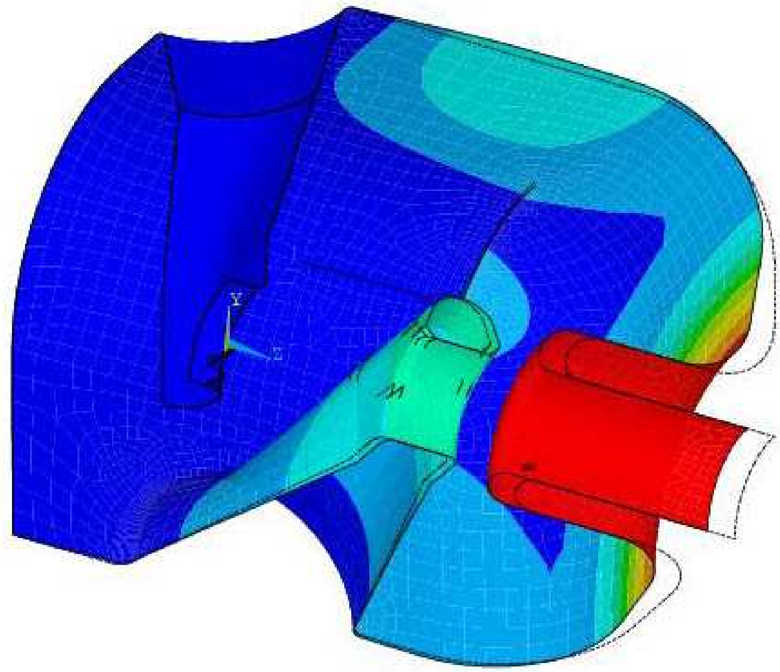
LORENZ FORCE DETUNING (B_{pk}=80 mT)

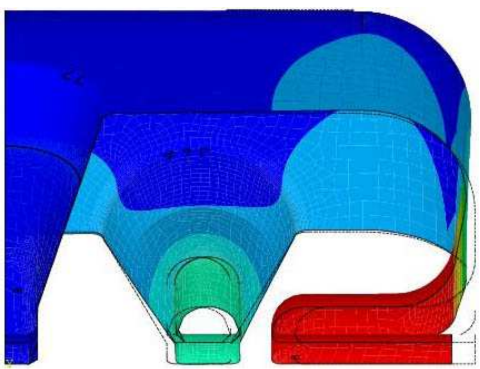
Mid-Spoke (0.0223 µm)



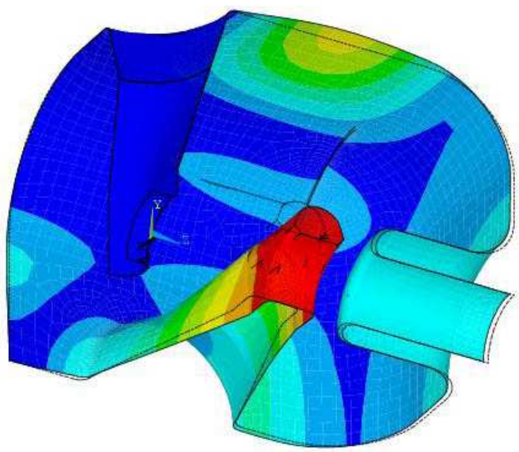
Spokes (0.478 µm)







Spokes + End Electrode (1.24 µ



Spokes + Walls (0.414 µm)

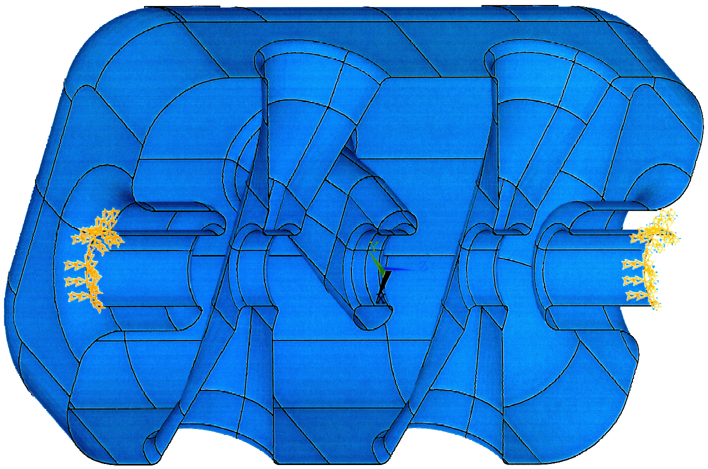
walls 2 mm

Spokes+Walls+End Electrode

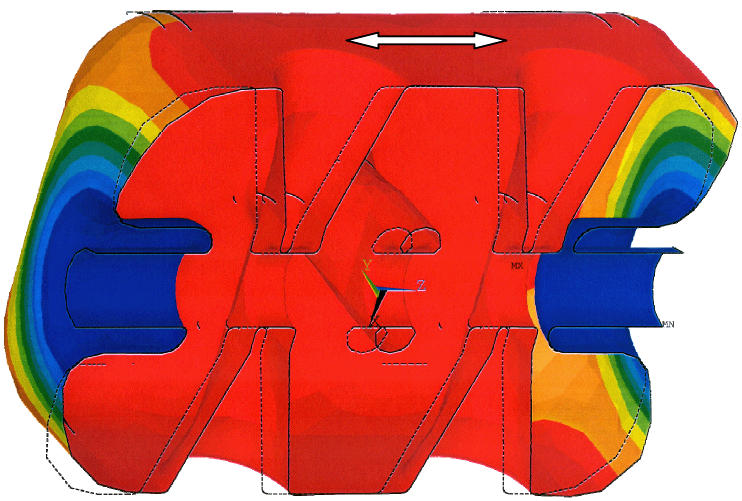
max deformation 1.31 µm

frequency shift 46 Hz/(MV/m)^2

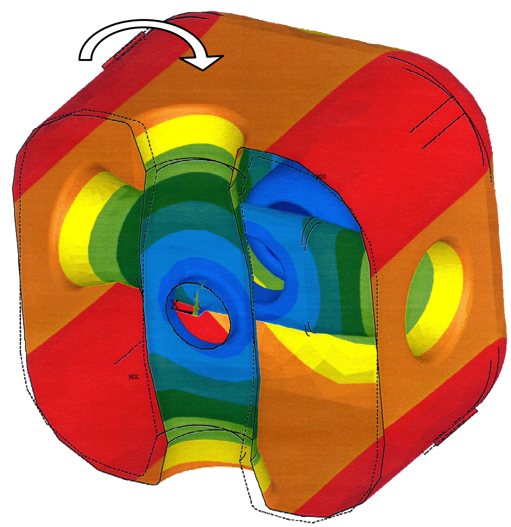
MECHANICS - MODAL ANALISYS



mode	freq / Hz
1	248.33
2	292.08
3	329.09
4	334.22
5	413.26

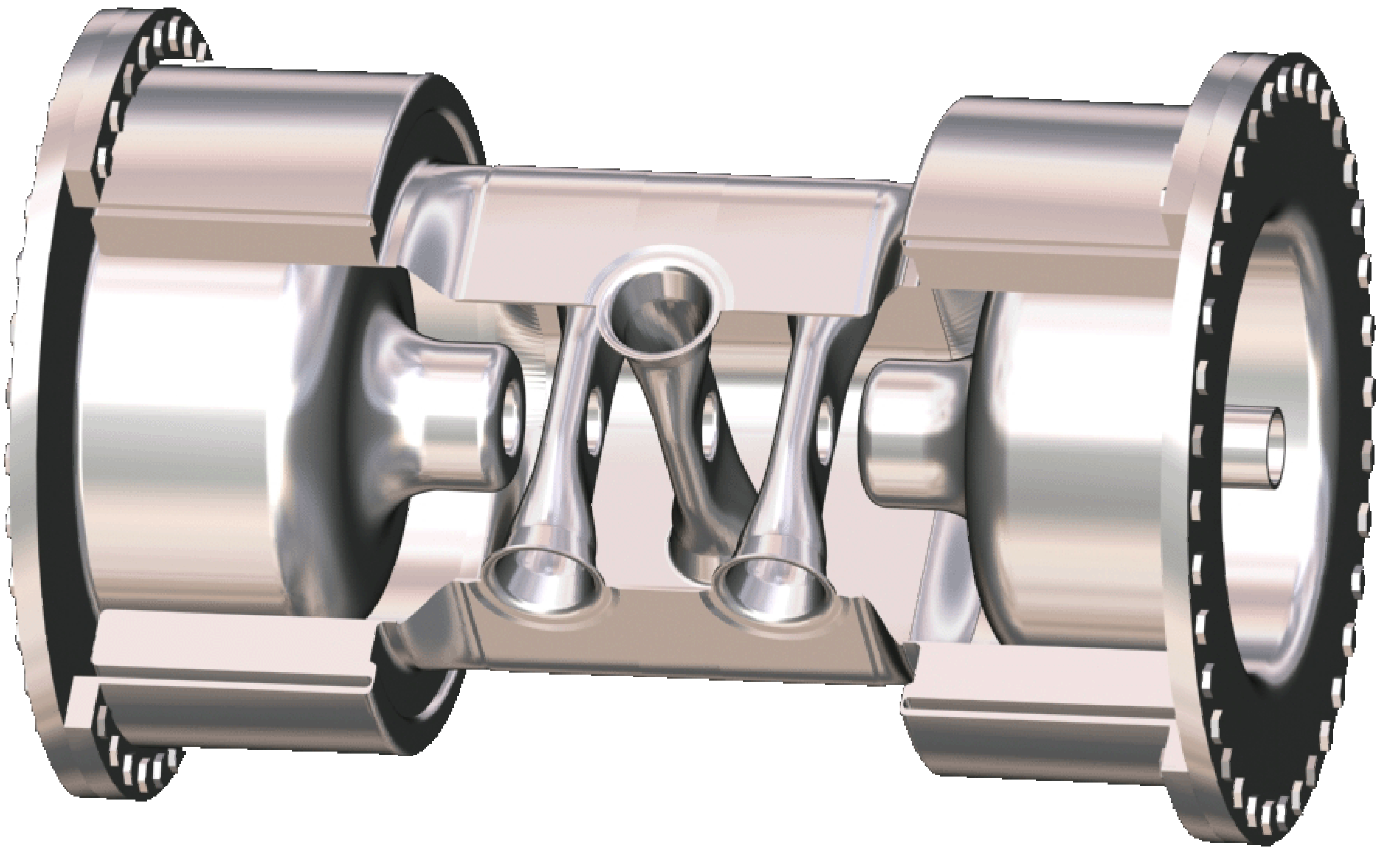


mode 1 - longitudinal

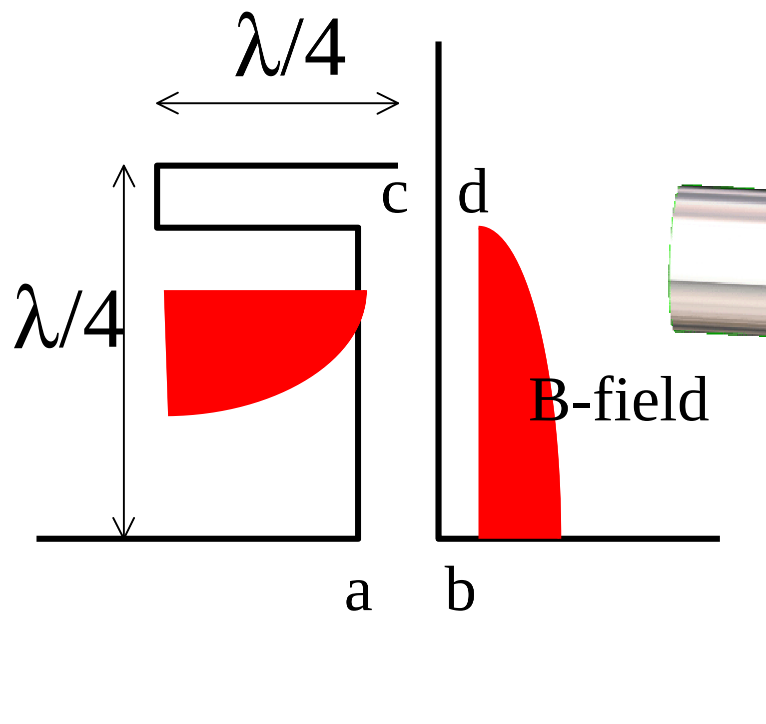


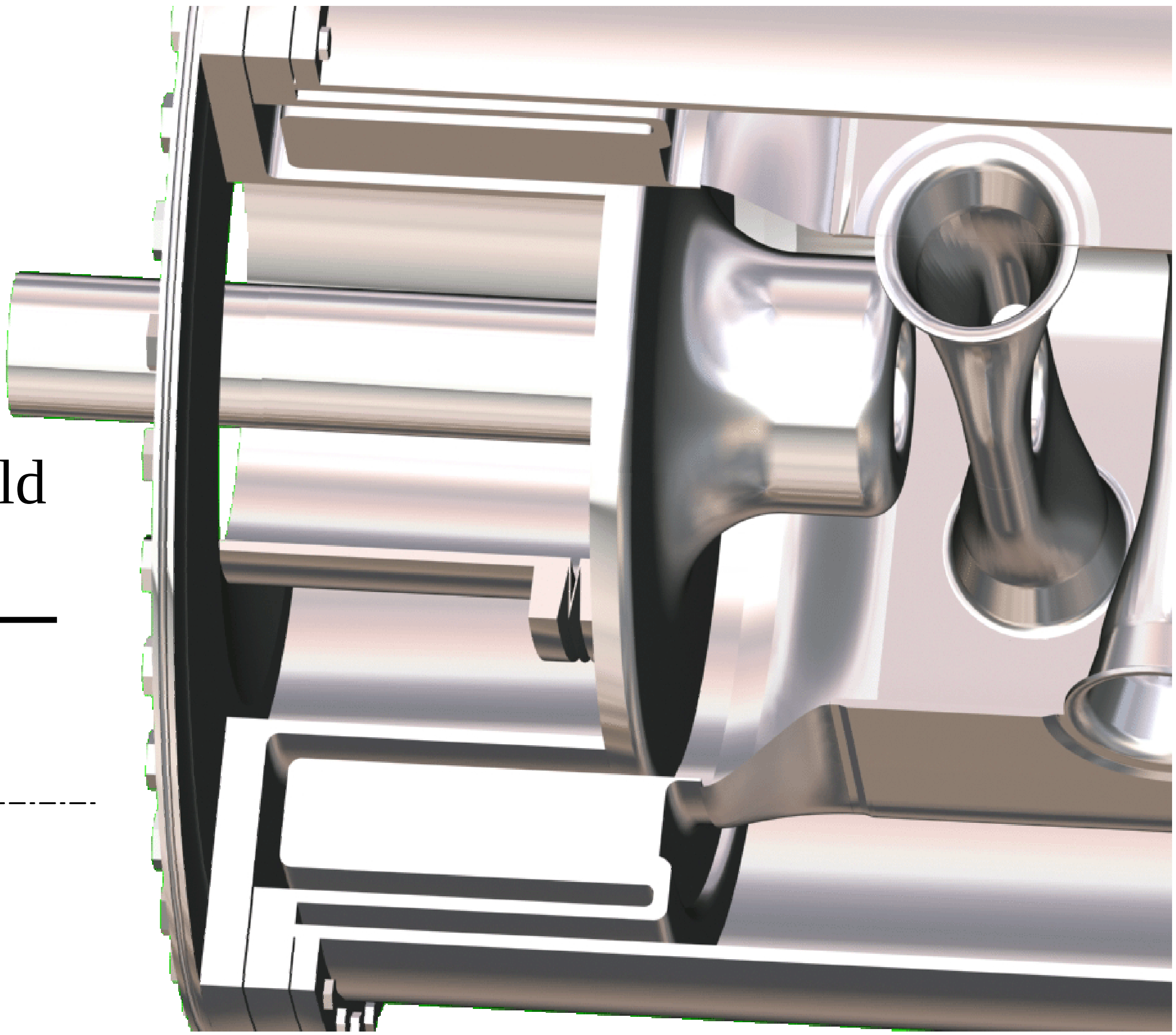
mode 2 - torsion

SC 4-GAP H-CAVITY (700 MHz , β=0.2)
dismountable tuning plate joint

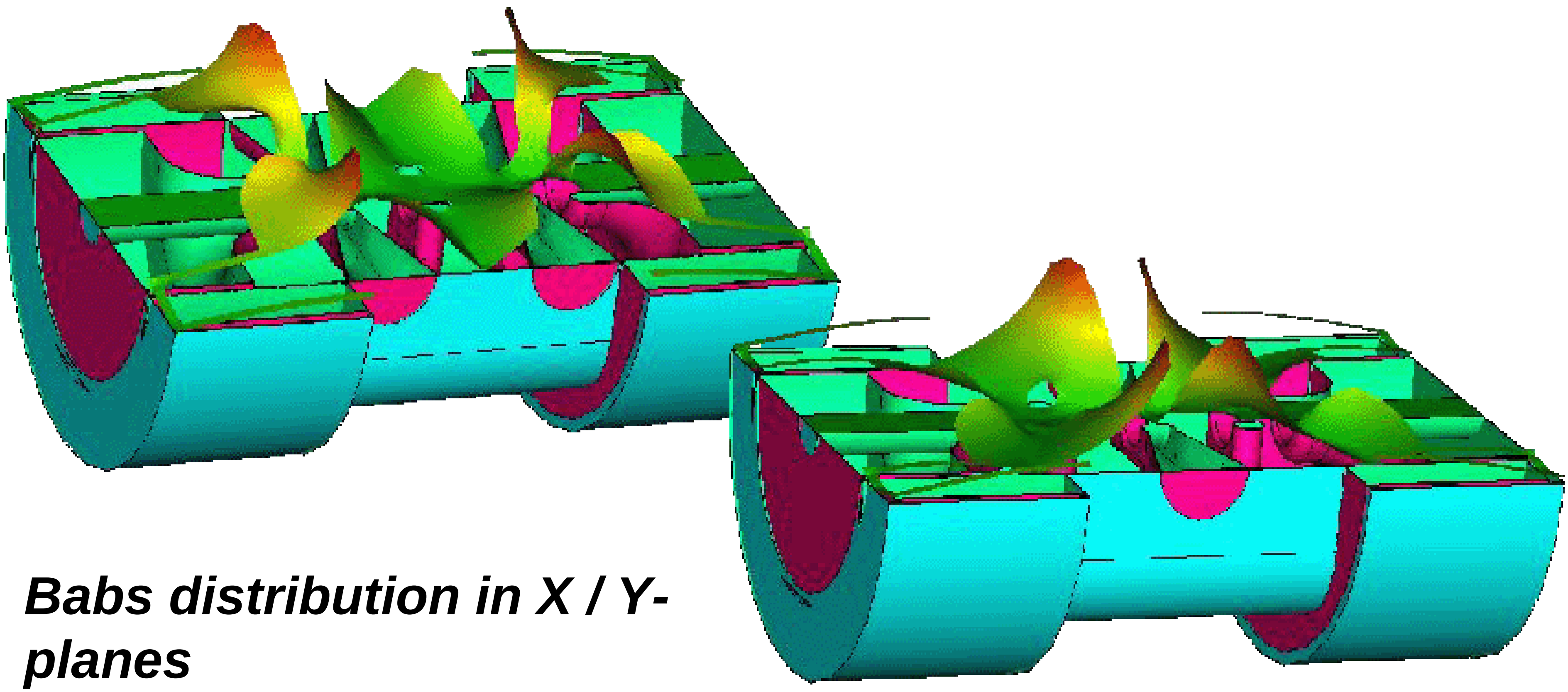


SC 4-GAP H-CAVITY (700 MHz , β=0.2)
dismountable tuning plate joint



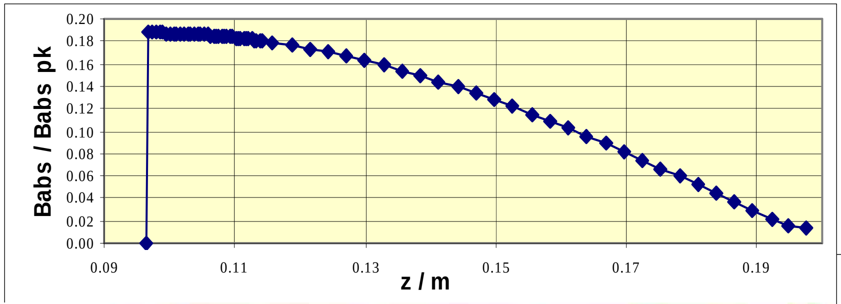


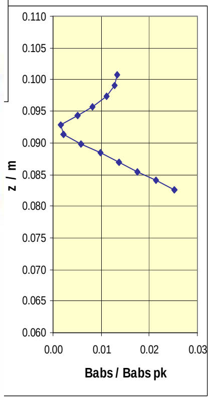
SC 4-GAP H-CAVITY (700 MHz , β=0.2)
dismountable tuning plate joint – e/m fields

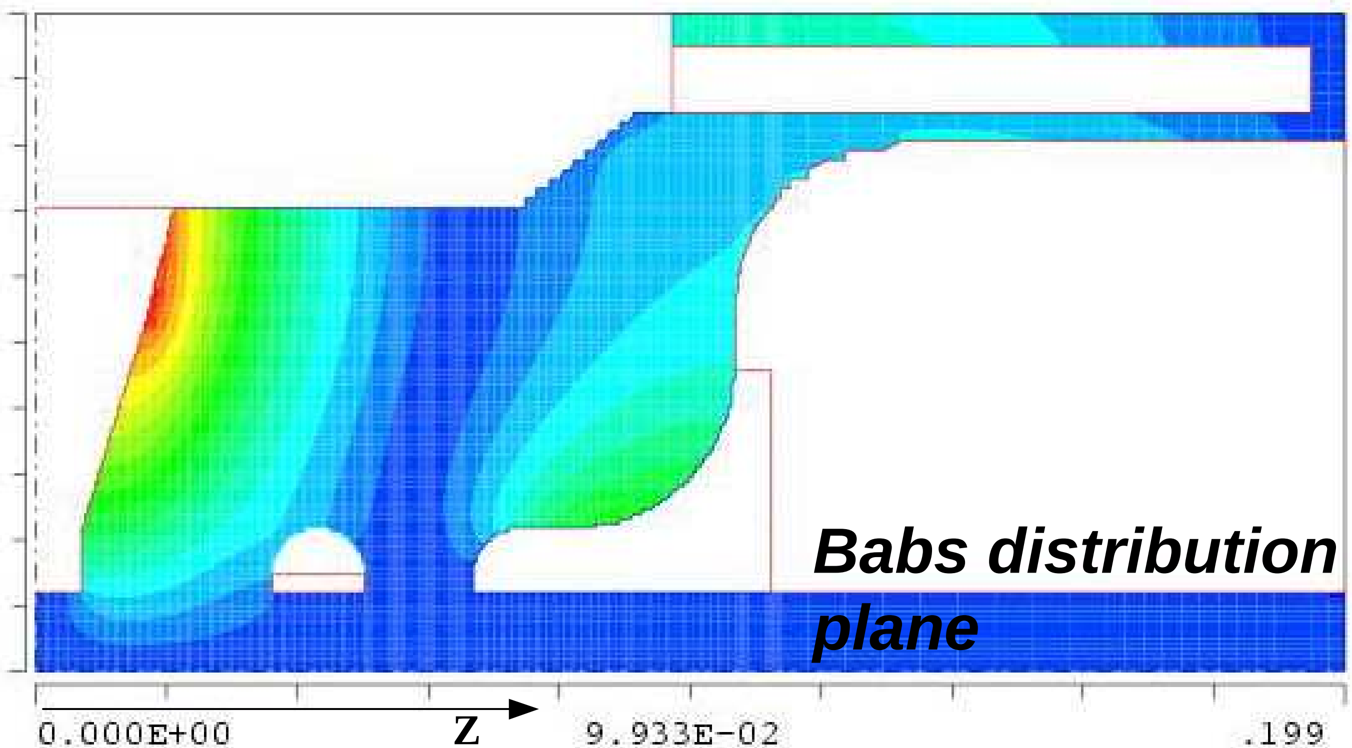


Babs distribution in X / Y-planes

SC 4-GAP H-CAVITY (700 MHz , β=0.2)
dismountable tuning plate joint – magnetic field



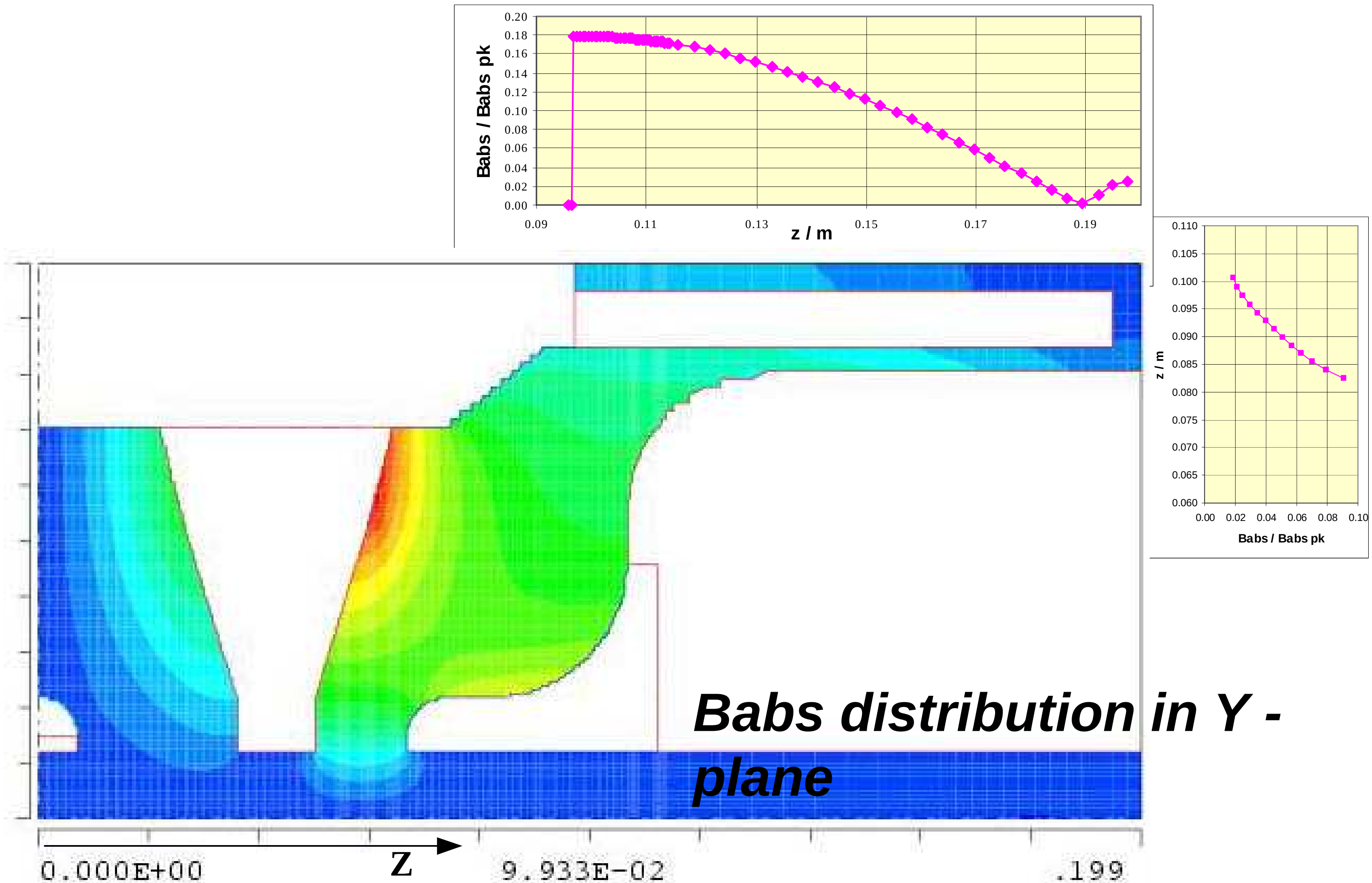




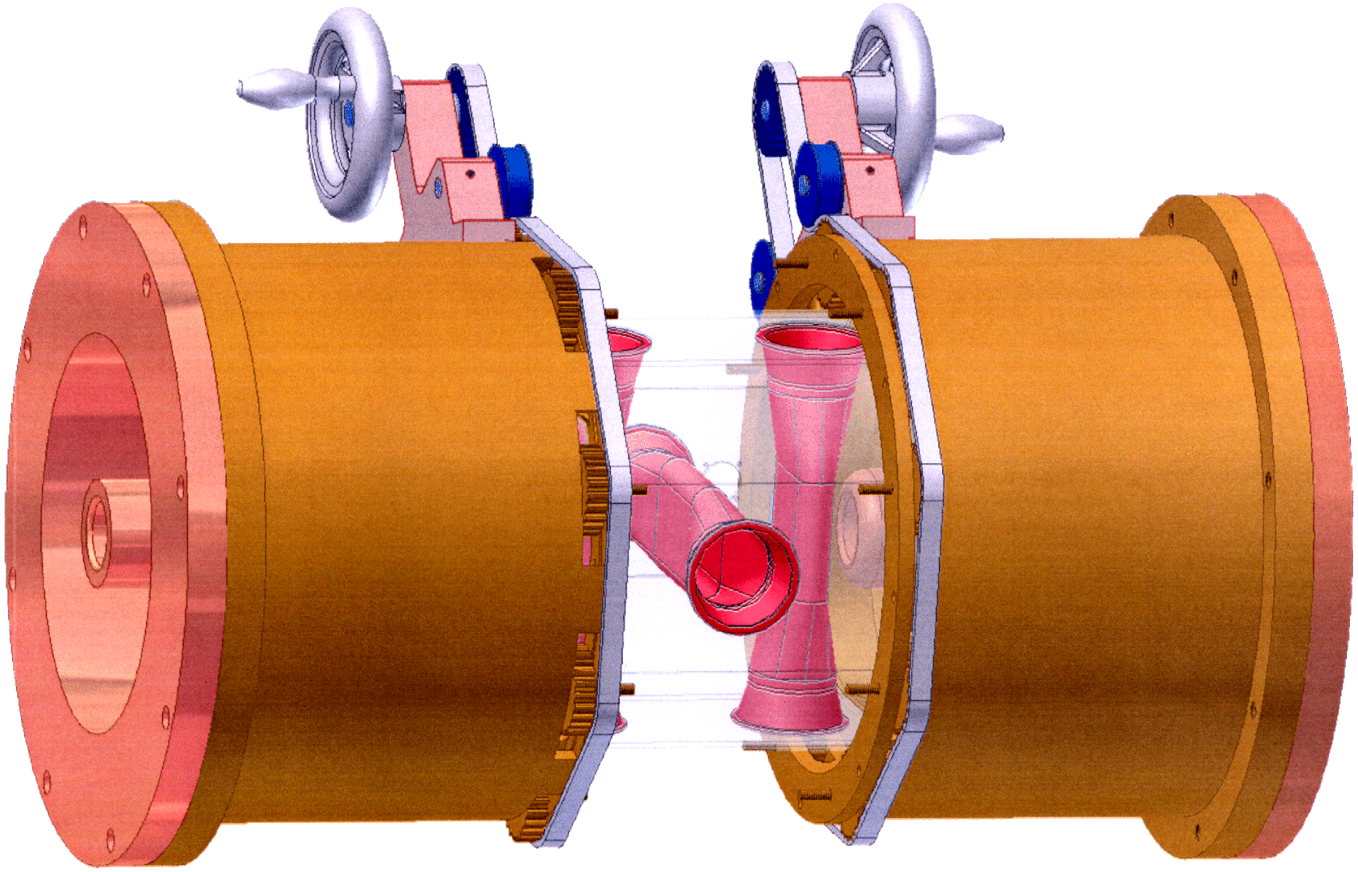
Babs distribution in X - plane

Forschungszentrum Jülich

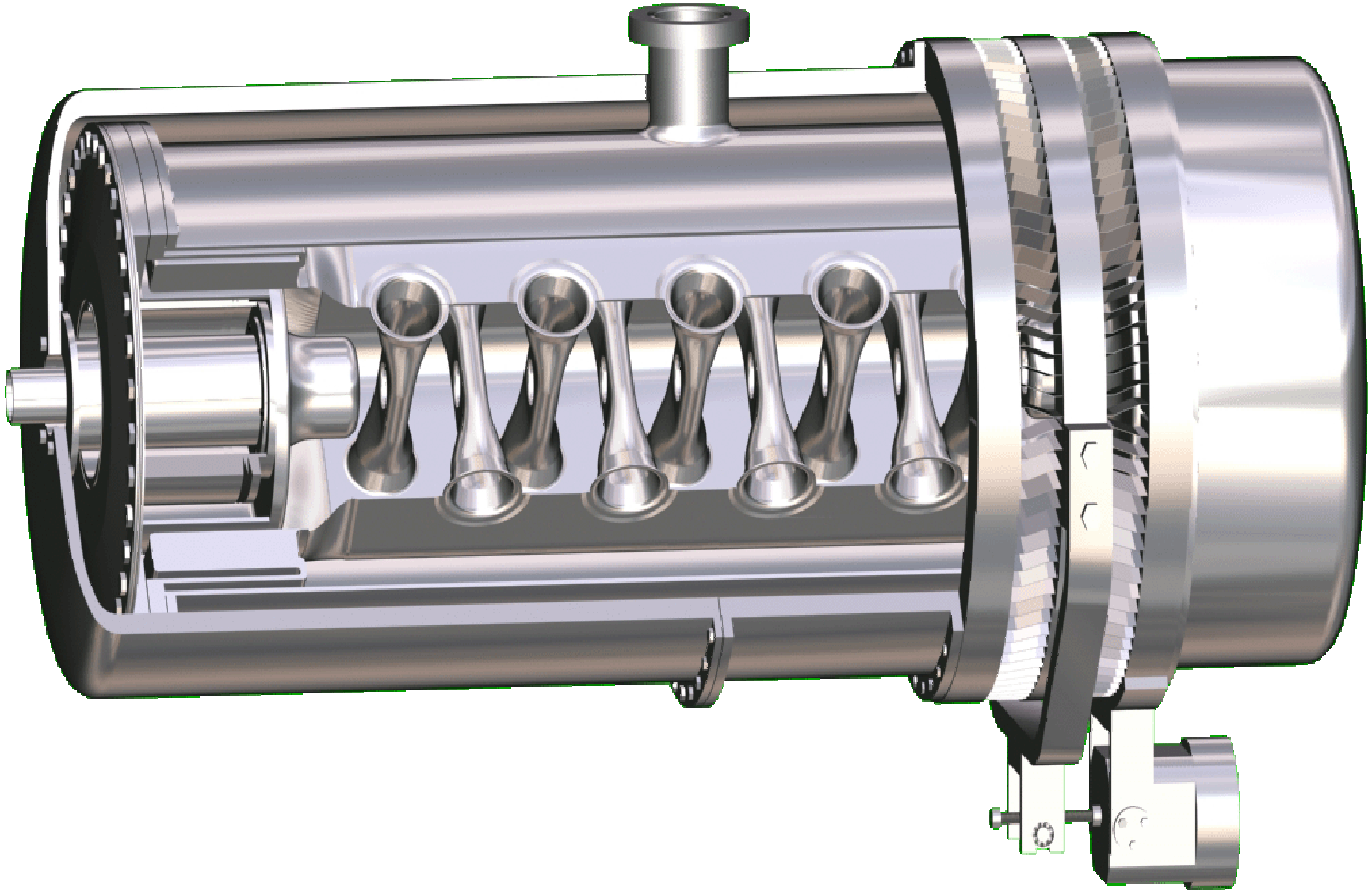
SC 4-GAP H-CAVITY (700 MHz , β=0.2)
dismountable tuning plate joint – magnetic field



SC 4-GAP H-CAVITY MODEL (700 MHz , β=0.2)
dismountable tuning plate joint



SC 10-GAP H-CAVITY (700 MHz , β=0.2) in cryomodule with DESY/INFN tuner



Discussion on "SC RF Cavity Activities at FZJ" by Evgeny Zaplatin

One of the unusual features in Zaplatin’s spoke designs was the use of choke-protected demountable endwalls. Questions from the audience asked about experience with using such chokes. Jefferson Lab had tried to use them on elliptical cavities. They had the expected low losses but major problems due to multipacting. KEK tried them for mounting their HOM couplers and saw strong multipacting due to desorbed gases. Zaplatin agreed that this concept needs more studies.

Questions were asked about the use of the proposed long 10-gap structures that have low velocity acceptance and stress the focusing lattice. Zaplatin indicated that the beam-dynamics for ESS was compatible with the length of the nominal 10-gap spoke resonator. But the beam-dynamics was never revisited for the added length due to the choke-protected endwalls.

Another aspect of using the long structures is the increased surface area. This increases the likelihood of defects in a structure that limit the potential performance of a cavity. Some people felt that this was an issue, but it was also pointed out that with better scanning techniques materials are better today than they were some years ago.

Zaplatin presented the design of a 700 MHz 3-gap spoke resonator that is build at Juelich right now. The fabrication is expected to be finished by the end of the year. A testing schedule is not known, as the test facility has to be shared with the higher priority tests for the SC injector for the COSY accelerator. Test should nevertheless be done by the summer of 2003.

Next the aperture of this resonator has been addressed. With 24 mm diameter this is seen as very small. Zaplatin pointed out that the nominal aperture for the ESS accelerator is 30 mm. Still, with a 10 mm beam size this is seen as challenging for halo issues. For example, RIA for a 3 mm beam uses 40 mm aperture.

Finally the reasoning for the 700 MHz frequency of this resonator has been asked. Zaplatin explained that this is driven by the ESS accelerator design. These spoke resonators are to be used after a funnel that requires doubling of the frequency of 350 MHz.

RF Design of Spoke Resonators for the AAA Project

Frank Krawczyk, LANL

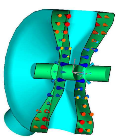
In this presentation the electromagnetic design of a 2-gap low-β superconducting spoke resonator for the AAA project is presented. The main emphasis is on the design strategy and conventions for picking specific geometry features. The choices of the explicit cavity dimensions for this resonator are driven by its use immediately downstream from the LEDA Radio-Frequency Quadrupole (RFQ). The resonator frequency is 350 MHz, its length corresponds to a geometric β (βg) of 0.175. An important aspect of the design is the integration of RF, mechanical properties and interaction with ancillary components, like the power coupler. The resulting RF properties, like Q, R/Q, peak surface fields and acceleration efficiency are very reasonable for such a low–β structure.

RF-Design of the AAA β=0.175 Spoke Resonator

Frank Krawczyk
LANL

Workshop on the Advanced Design of Spoke Resonators

Los Alamos, NM, USA
October 7 and 8, 2002



Introduction

- Presentation covers a low-β spoke resonator with:
  - 2 gaps, β=0.175, 350 MHz, integrated ports for high current operation

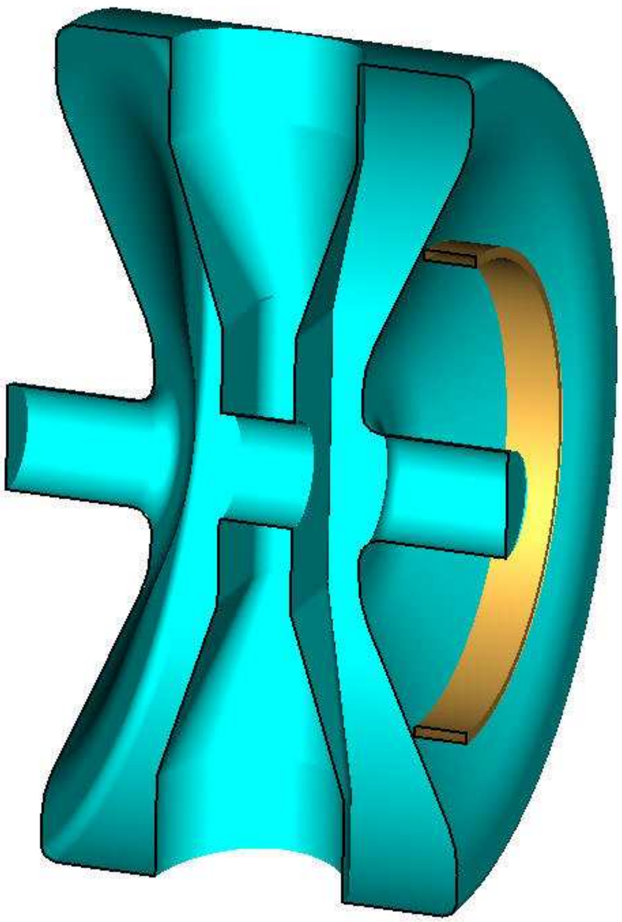
- The following issues will be covered:
  - Simulation tools -RF Design-
  - Design strategy
  - Integration of RF and mechanical design
  - Other conventions
- Results will be presented for
  - Cavity geometry
  - RF parameters of the cavity
  - RF-Interaction with the coupler
  - Thermal issues of the coupler/cavity interface

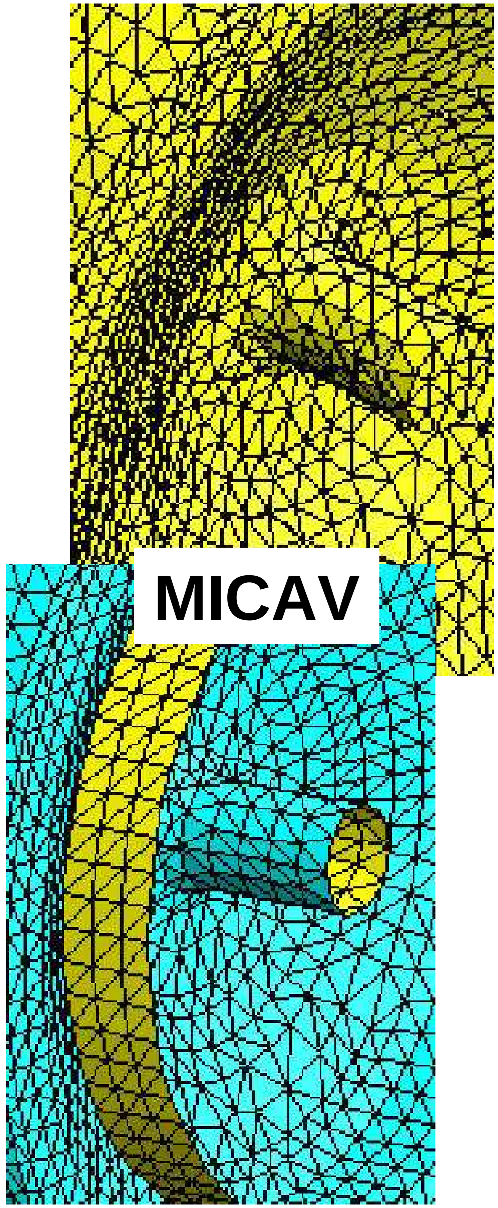
Simulation Tools -RF Design-

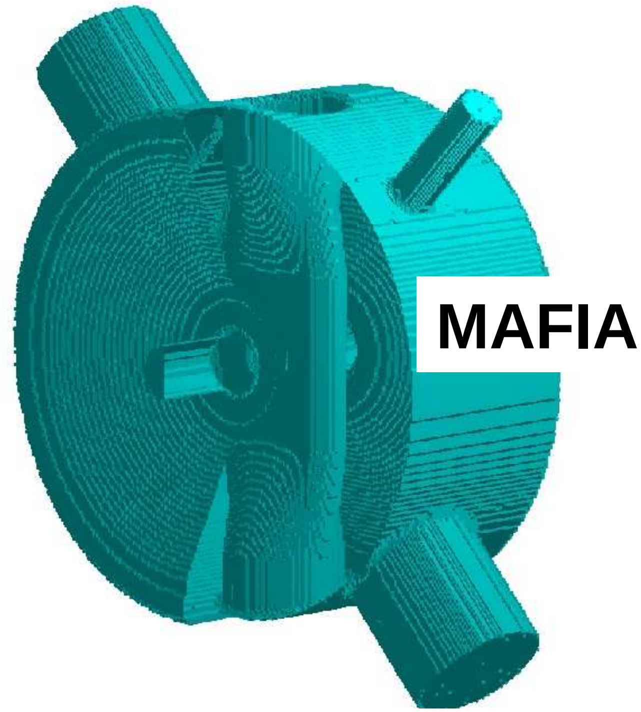
MAFIA	MWS	MICAV
Known reliability	Fairly new	
Extensive post-processing	Post-processing by user written VBA	Post-processing by external user programs
Geometry import from CAD		
Poor surface representation (requires fine meshes) slow	Accurate surface representation (requires moderate meshes) fast	
Manual mesh improvements give good results	Overall very efficient tool. Modeling difficulties for complex geometry, Inaccurate peak surface fields.	RF models compatible with mechanical (COSMOS/M) models Limited experience with quality of results

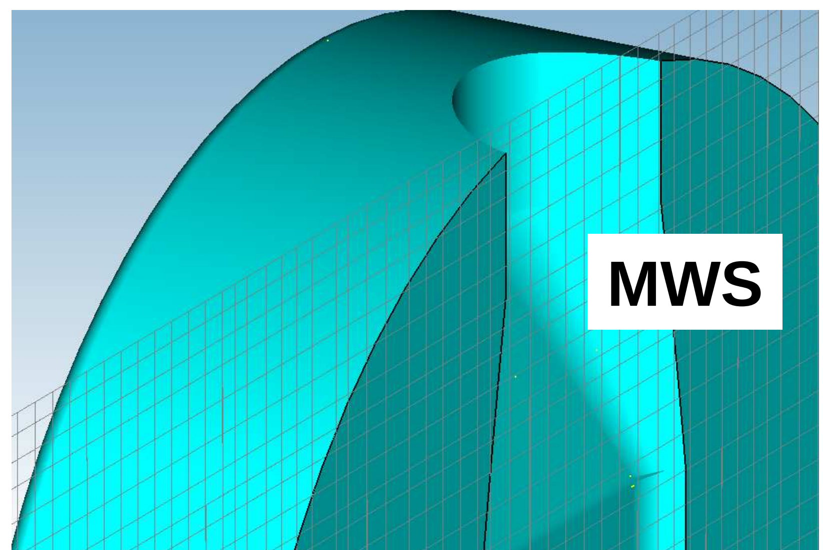
Simulation Tools

CAD





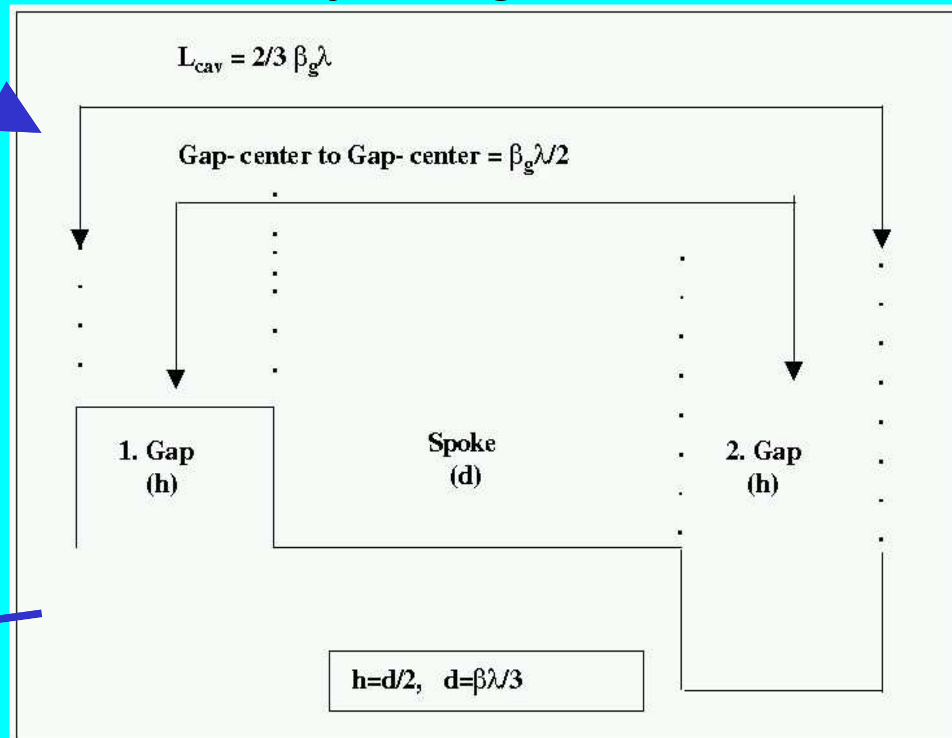




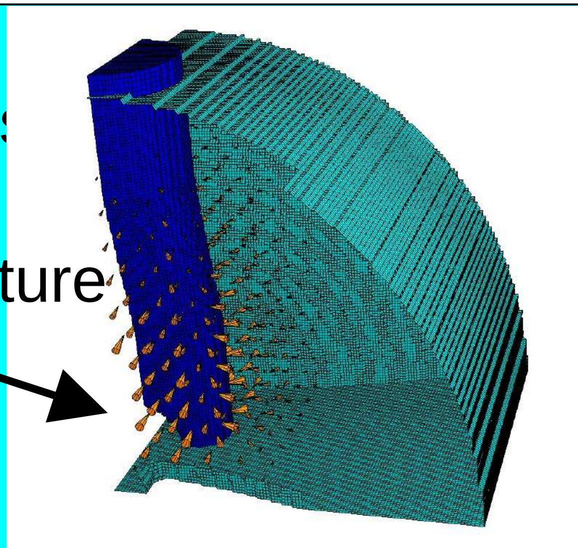
Design Strategy

1. Cavity Diameter ~ λ/2

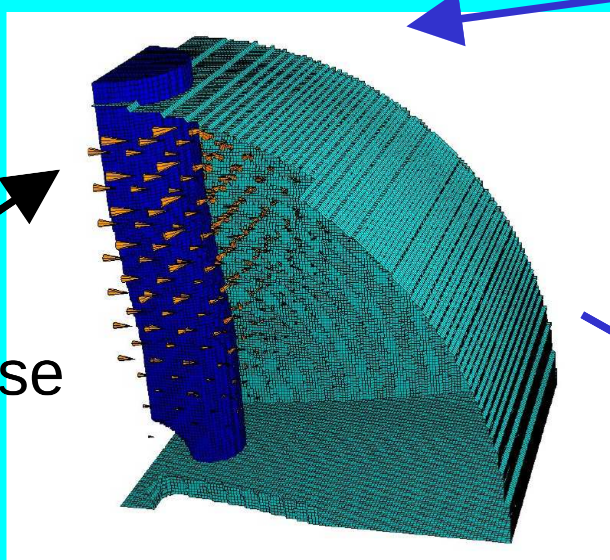
2. Set Cavity Length



3. Peak Fields



E_{peak} @ aperture



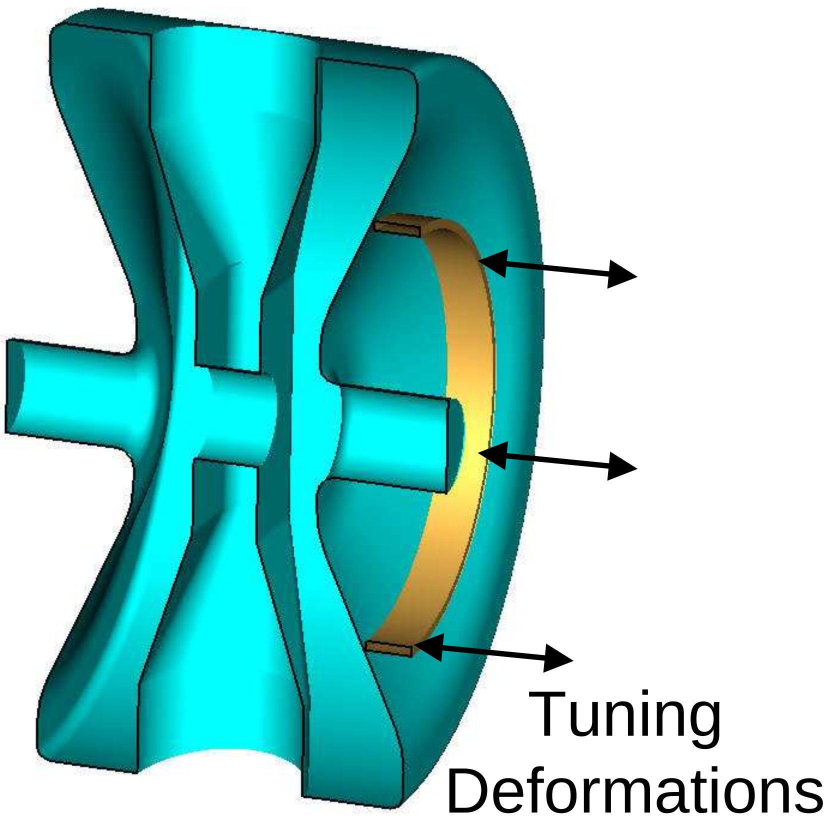
H_{peak} @ base

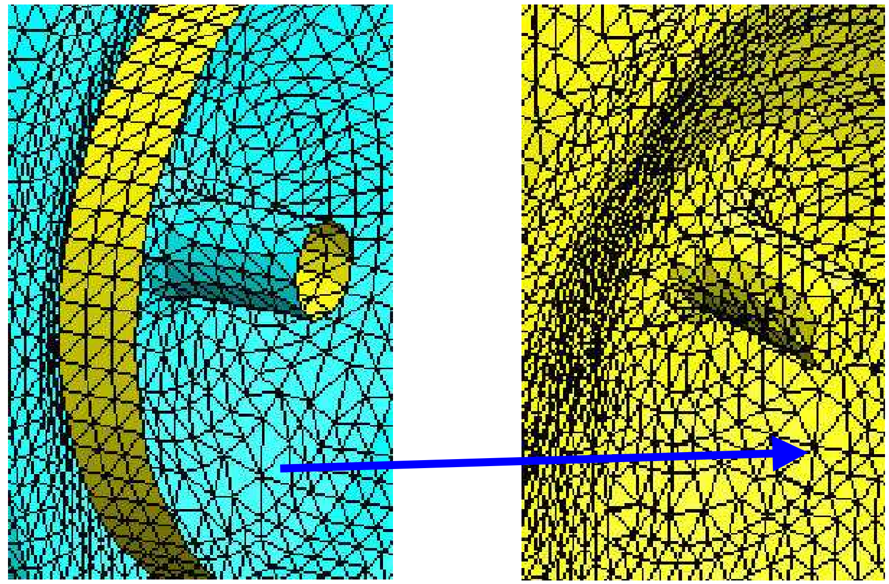
4. Further steps:

- Optimize Endwall Shape
- Incorporate port attachments
- Tune cavity by setting radius

RF and Structural Design Integration

RF Effects of Deformations:
Tuning Sensitivity/ Forces

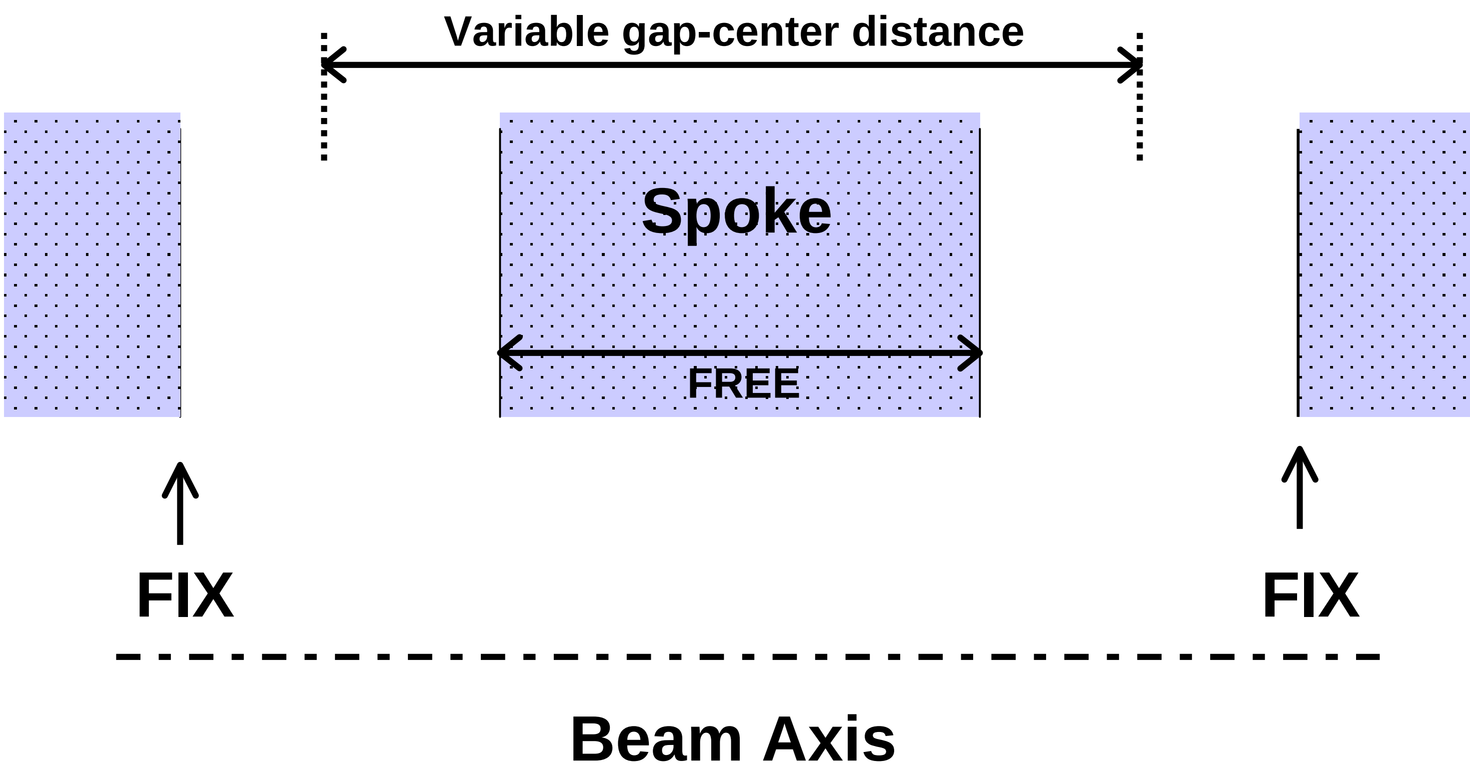




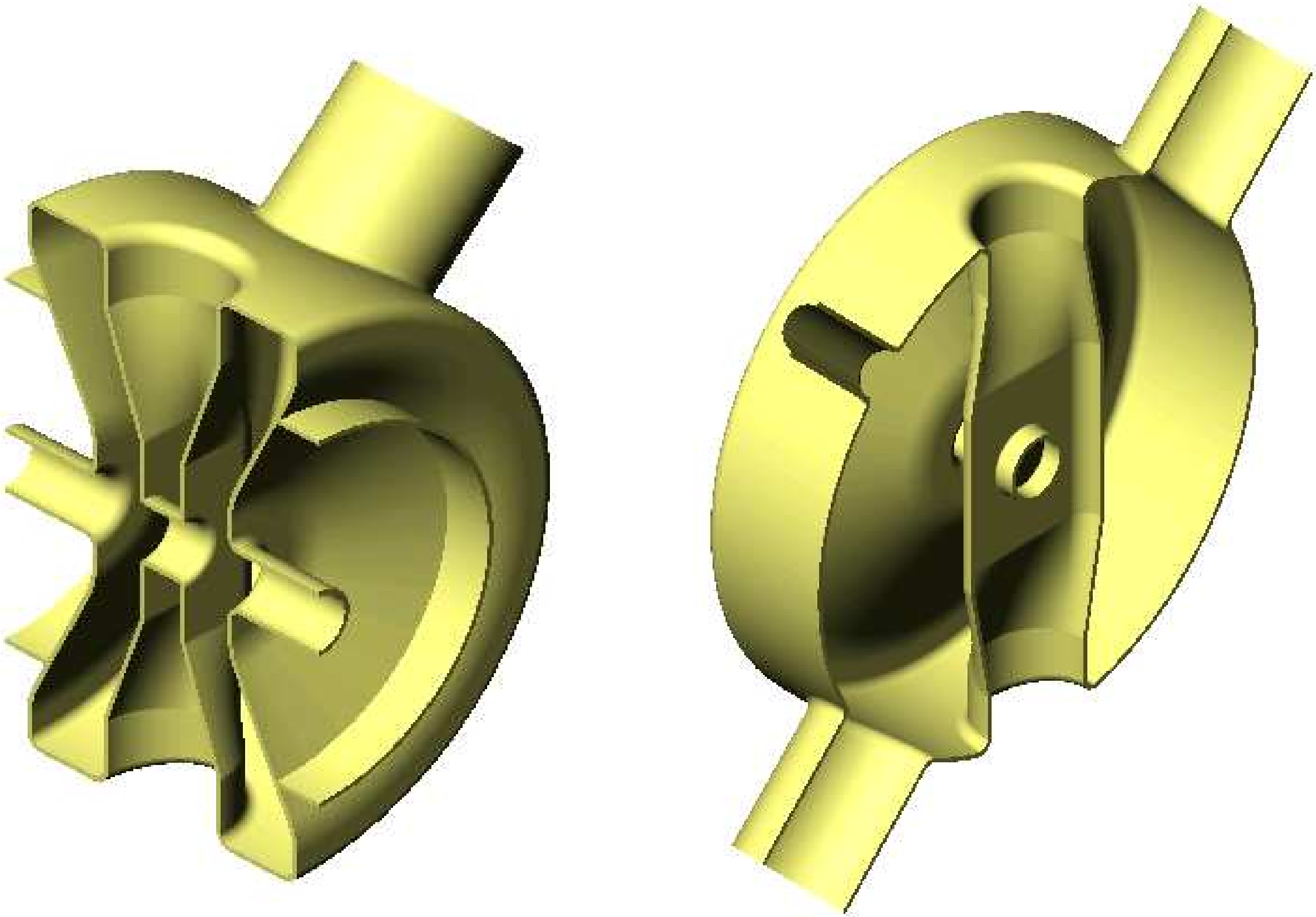
Common nodes allow recalculation
of RF-case without re-meshing
(reduces discretization error)

Conventions

1. Maintain circumference along spoke
2. Keep overall gap-to-gap length to 2/3 $\beta\lambda$
3. Allow deviation from d = 2* gap length

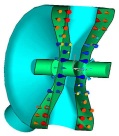


Geometry



RF Results

Q_0 (4 K)	1.05E+09 (for 61 nΩ)
T (β_g)	0.7765 (β_g=0.175)
T_{max}(β)	0.8063 (@ β=0.21)
G	64.1 Ω
E_{pk} /E_0T	2.82
H_{pk} /E_0T	73.8 G/MV/m
P_{cav} (4 K)	4.63 W @ 7.5 MV/m
R/Q	124 Ω

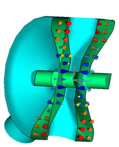


RF Parameter Comparison

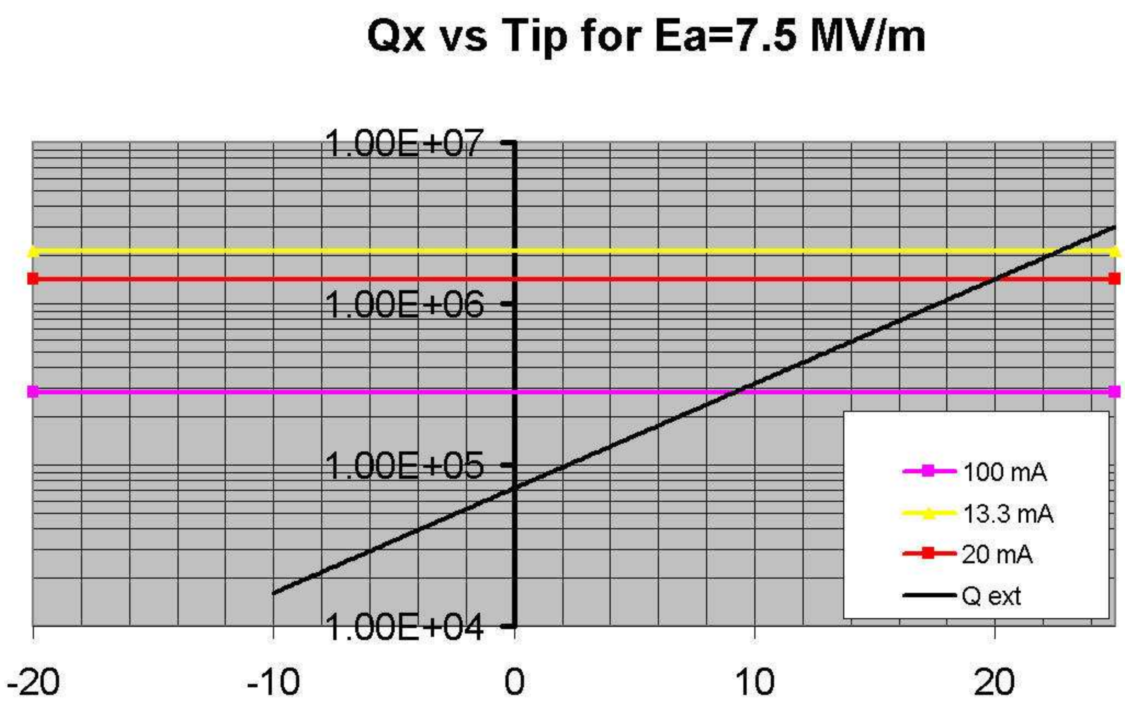
	0.175	0.200	0.340	ANL 0.3	APT 0.64
Frequency [MHz]	350	350	350	350	700
T_g	0.777	0.787	0.769	-	0.650
T_{max}	0.806	0.790	0.777	0.910	0.700
Q_0 (61/16 nΩ)	1.05E+09	1.34E+09	1.28E+09	1.01E+09	9.40E+09
ZT^2/Q [Ω]	124	214	318	295	191
E_{pk}/E_0T	2.82	< 3.60	< 3.47	3.18	3.38
B_{pk}/E_0T [G/MV/m]	73.8	< 96	< 104	85	70
G [Ω]	64.1	94	90	70.7	149
Q_x (nom.)	1.90E+05	1.10E+05	1.10E+05	-	2.00E+05
E_0T (nom.) [MV/m]	7.50	5.00	5.00		6.00
B_{pk} @ E_0T [G]	554	TBD	TBD	-	420
B_{pk} in testing [G]	1040	-	-	1000	840

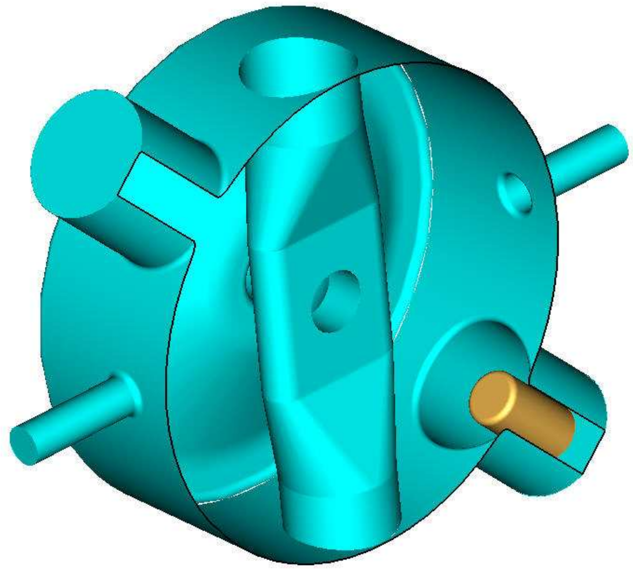
Optimized Geometry

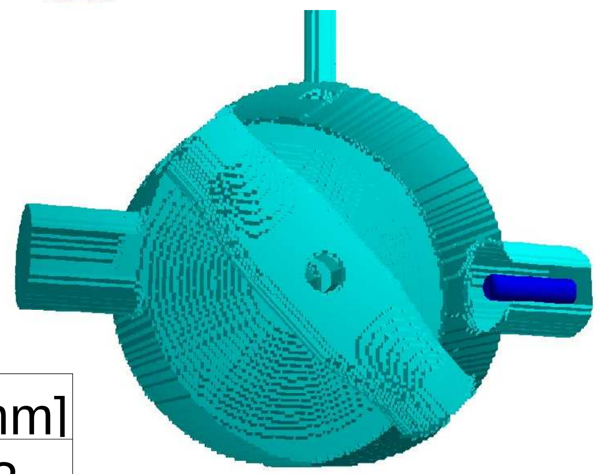
Non-Optimized Geometry



Design Integration: Coupling Evaluation



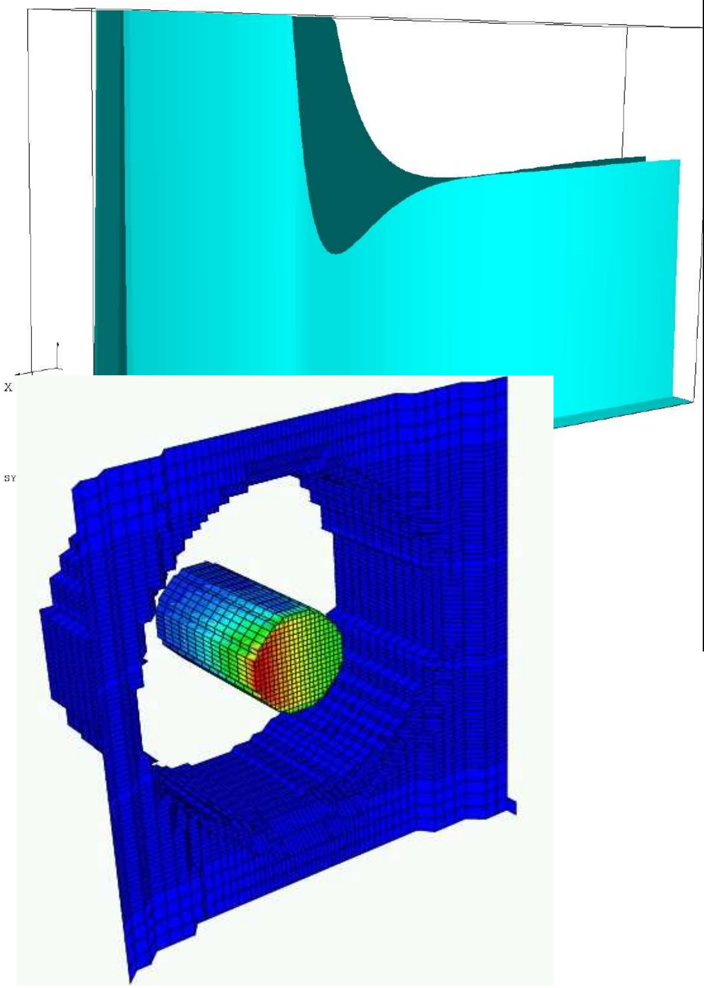


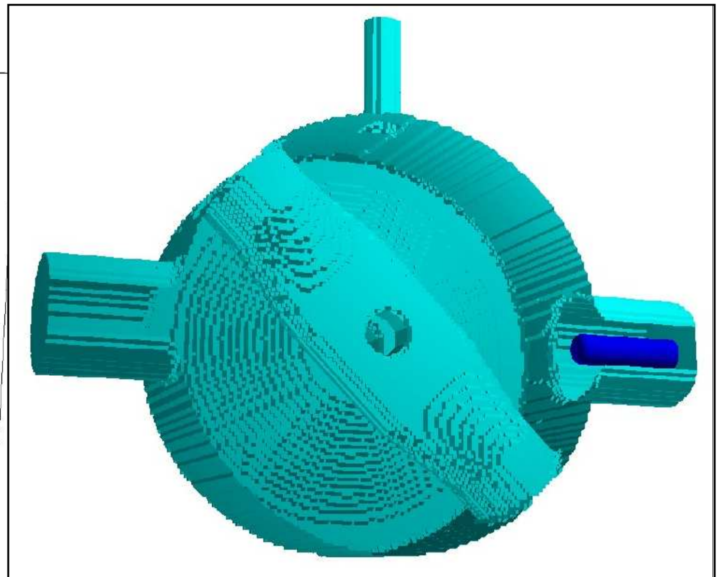


Goal: 1. Tip position
2. Frequency

I [mA]	Q_x	Δf [kHz]	z [mm]
13.3	2.13E+6	reference	23
20.0	1.42E+6	-200	20
100.0	2.83E+6	-970	9

Integration Issues: TW Solution/ Losses





MAFIA Model

Radiative losses @ 8.5 kW
(7.5 MV/m, 13.3 mA)

$p_{tip\ max}$	4.82 W/cm^2
$P_{tip\ total}$	25.2 W
T_{tip}	52^o C
$P_{thermal}$	0.5 W

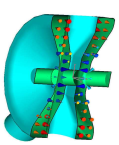
Question:
Accounting for loss contributions to cavity Q ?

Q_0 w or w/o tip losses, tip 6 cm withdrawn

P_{cav}	P_{outer} (SST)	$P_{antenna}$	Q_0	ΔQ_0
1.0 W	-	-	3.83 E8	-
1.0 W	0.051 W	-	3.64 E8	-4.8 %
1.0 W	0.051 W	9.9 W	3.49 E7	-91.0 %

Summary/Outlook

- The design of a low β spoke resonator has been presented. The RF-parameters indicate the potential for a high gradient operation.
- While the design approach seems to be similar to the approaches others have done, there are details that need review.
- The main issue for discussion is the integration/interface issue between cavity and coupler, especially for high-current applications.



Discussion on "RF Design of Spoke Resonators for the AAA Project" by Frank Krawczyk

The design approach for the LANL spoke resonator did not maintain the $\beta\lambda/2$ gap-center to gap-center distance. Krawczyk explained that this originally was totally arbitrary. He did not consider the change in β when he did the optimization. This approach was not corrected due to the good parameters for the beam velocity range where this resonator was supposed to be used. Delayen pointed out that in his nomenclature this resonator would be considered a β=0.21 resonator. In response Krawczyk expressed a preference for a geometric criterium for the β of a structure. He sees a disadvantage in needing to know the RF fields to determine the maximum transit time factor to know the structure's β.

Related to the power coupler antenna that is proposed to be cooled by helium gas at room temperature, Shepard mentioned that ANL with the ATLAS project has experience on how to feed a cooling stream to a coupler at 80 K. This should not only reduce the heat loads at the cavity, but also the outgassing into the cryogenic environment.

Kelley expressed worries about adding an additional cooling stream to the cryomodule. In the end time and schedule will probably drive the design.

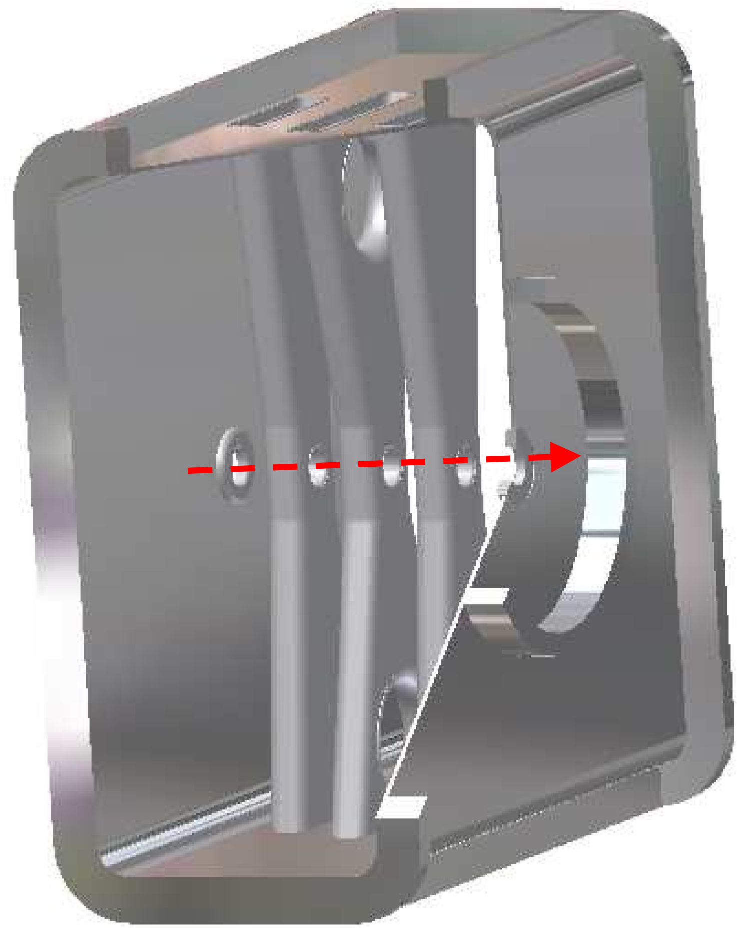
The Ladder Spoke Resonator at INFN Legnaro

G. Bisoffi, INFN-Legnaro

A novel superconducting (sc) structure is proposed, to accelerate a high intensity proton beam in the energy range 5÷20 MeV. The framework is that of the EURISOL driver linac. The design is rather attractive from the point of view of both rf efficiency and technological aspects of manufacture. Results of M.A.F.I.A. simulations are given.

The Ladder Spoke Resonator at INFN-Legnaro

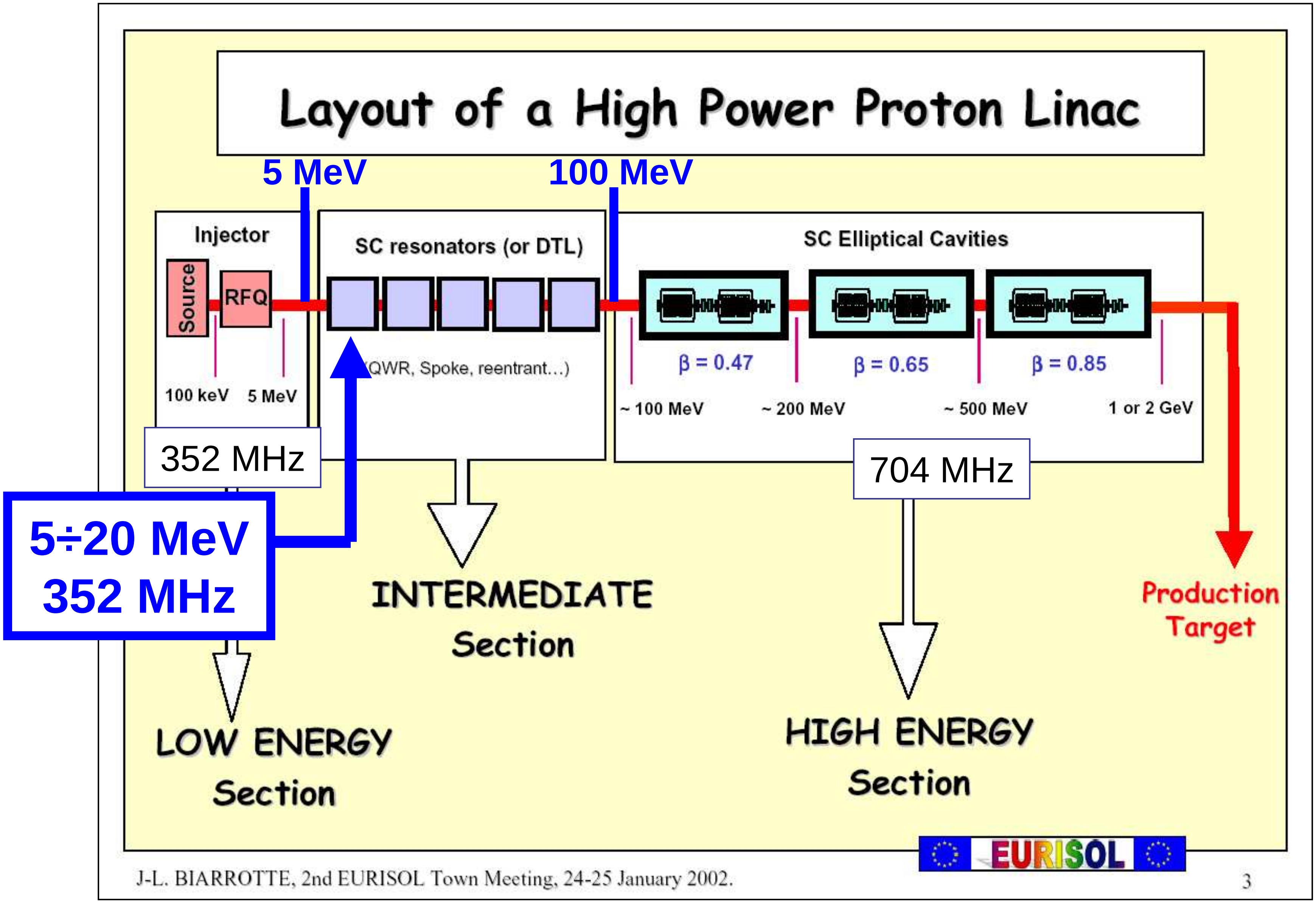
*V. Andreev, **G. Bisoffi**, A.Pisent,*
E. Bissiato, M.Comunian, E. Fagotti
INFN – LNL
T. Shirai
ICR, Kyoto University



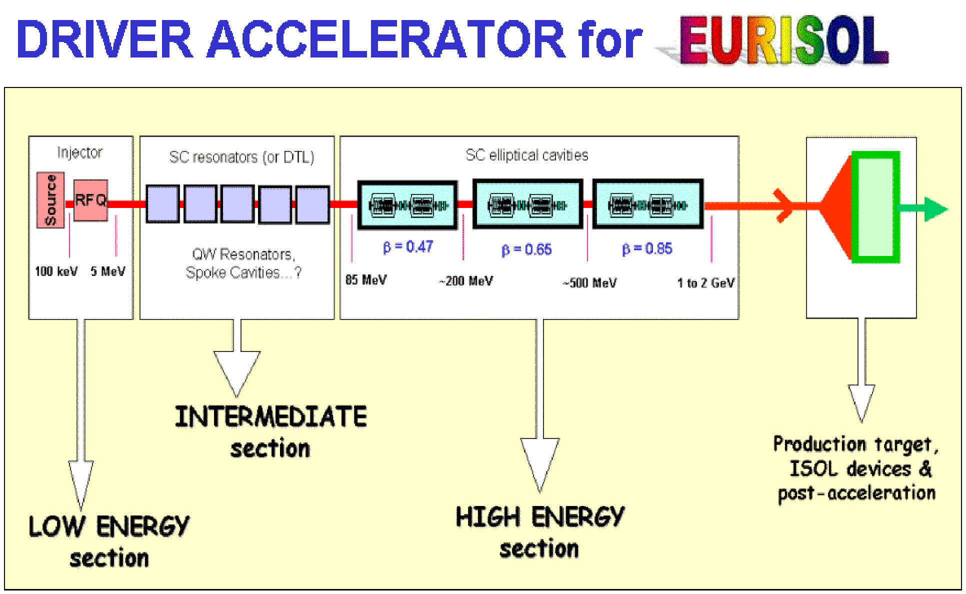
An easily accessible SC resonator
for a **5 mA proton accelerator**
352 MHz, 4 gaps, β_0 = 0.12 & 0.17,
5÷20 MeV range

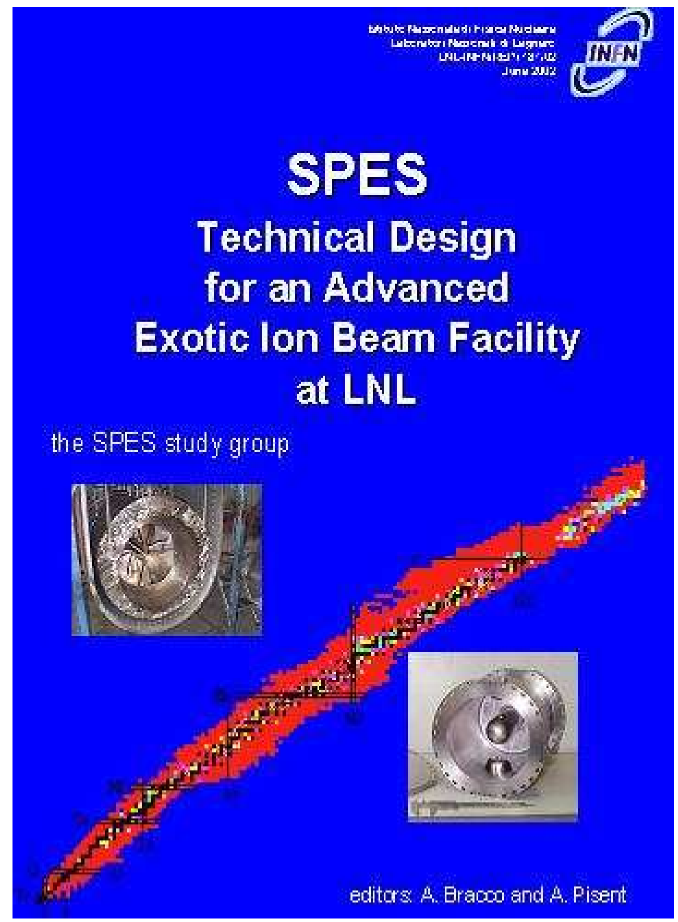
Framework
Linac design
E_z flatness = B-field = Large flanged joints
= RF Coupling = f-tuning
Outlook

Framework: β = 0.1÷0.2 SC cavities for 5 mA p linac

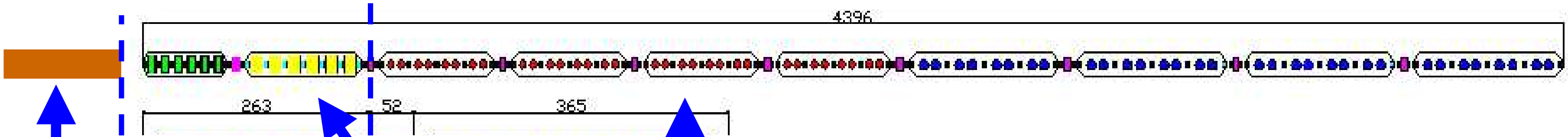


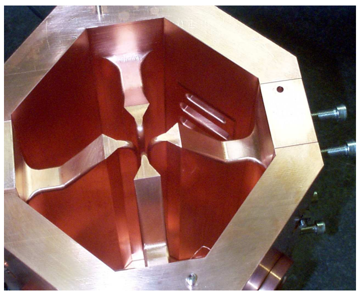
5 mA p superconducting linacs for RIBs production (but also ADS demonstrators..)

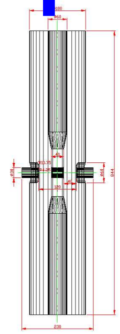


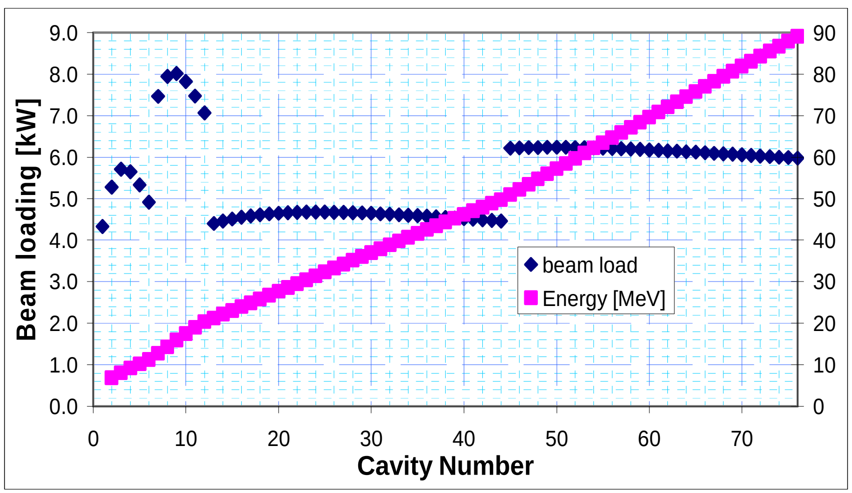


5 mA superconducting linac (SPES-EURISOL)



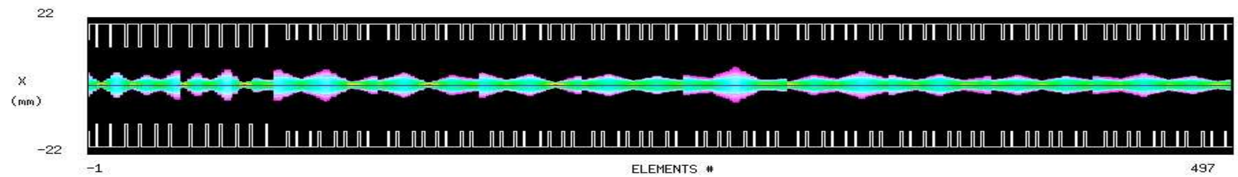




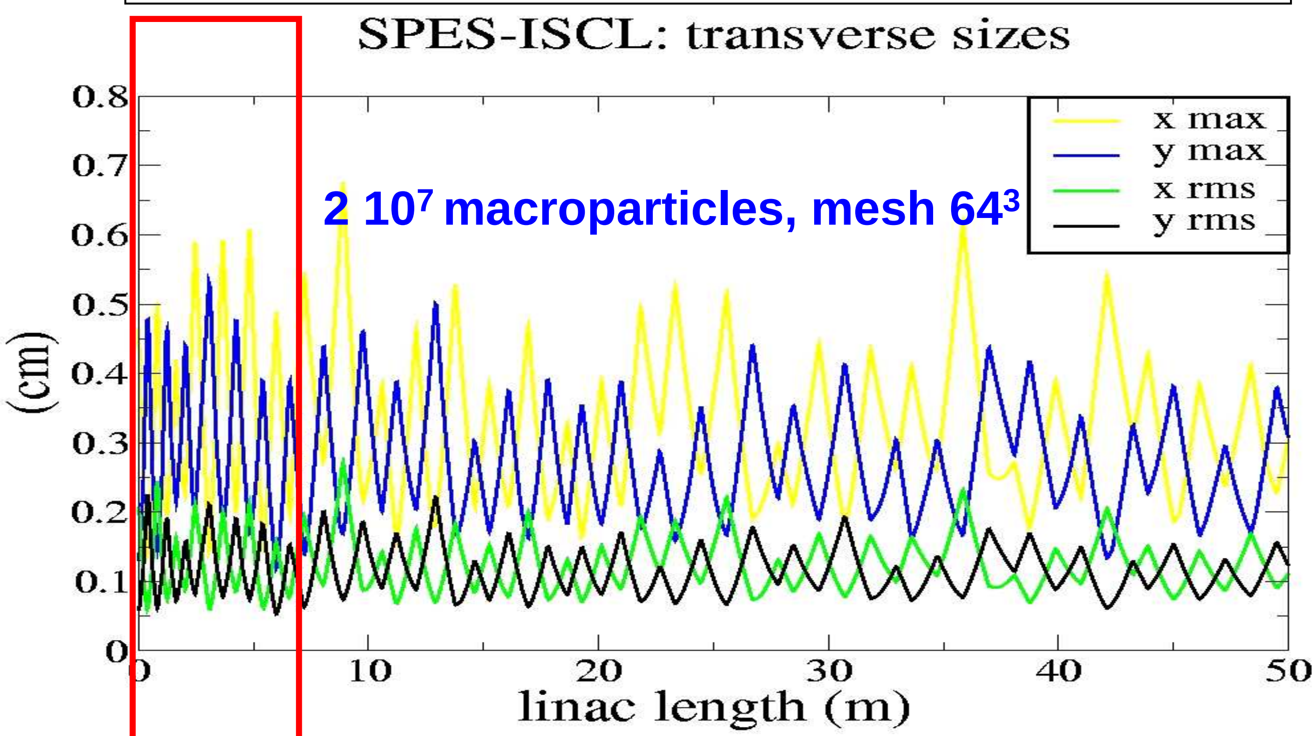


Total length	44	m
Final energy	89	MeV
Synchronous phase min/max	-35/-25	deg
Average acceleration	1.90909	MeV/m
Number of cavities	76	
Number of Quadrupoles	54	
Max. Quadrupole gradient	40	T/m
Quad aperture/length	2/5	cm
Current limit (losses<10-5)	>50	mA
RF dissipation	760	W(@4.5K)
Beam loading	420	kW
RF sys. pwr. cons. (h_{RF}=50%)	840	kW
Static cryo. losses (10 W/m)	440	W
Cryo. sys. cons. (h_{cryo}=1/500)	600	kW
Mains power	1440	kW

Beam Envelopes with the 5 mA p beam



$\varepsilon_{T,in}$(norm) = 0.2 mm mrad, $\varepsilon_{L,in}$ = 0.2 MeV deg

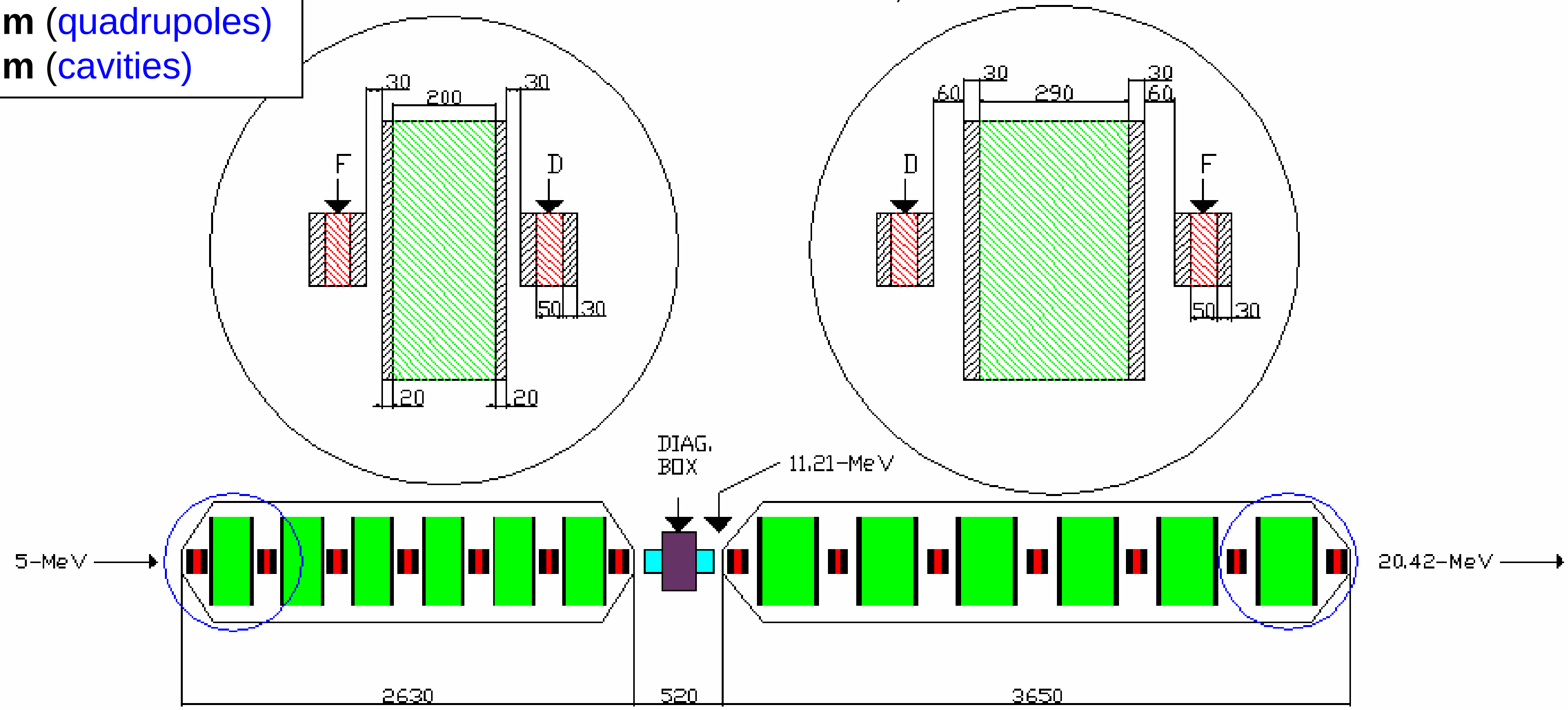


(Section with **12 ladder resonators**
5÷20 MeV, Length = **7 m**)

Twelve 4-gap Resonators in 2 Cryostats

Beam bore Ø:
40 mm (quadrupoles)
25 mm (cavities)

Needed $\mathbf{E_a = 5.8}$ **MV/m**, $\phi_{s,av} = -30^o$, $\mathbf{L_{eff} = 2\beta_0\lambda}$



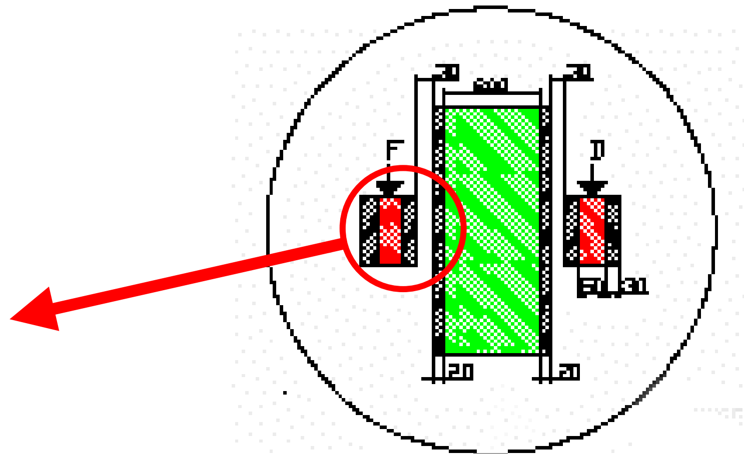
$\beta_0 = 0.12$

$\beta_0 = 0.17$

Strong transverse focusing in the first cells (97º per FODO)
to avoid the fast exponential growth of the **parametric resonance**

The focusing element: a superferric quadrupole

A Superferric Quadrupole for use in an SRF Cryomodule, F. Zeller[1], J. C. DeKamp[1], A. Facco[2], T. L. Grimm[1], J. Kim[1], and R. Zink[1]
[1] ***NSCL-MSU*** [2] ***INFN - LNL.***



Properties

Effective length 50 mm

Radius 20 mm

Gradient 31 T/m

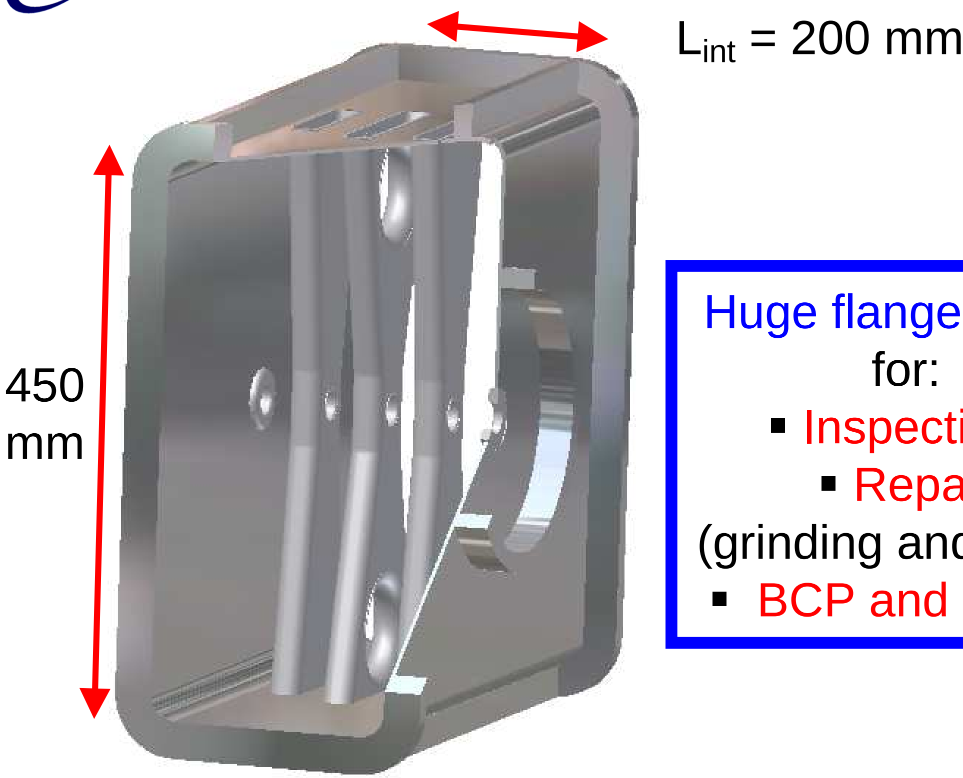
Current (2-D calculation) 63 A

H_q field in the resonator < 0.05 mT

Why quadrupoles? Homogeneous to preceding RFQ and following linac scheme

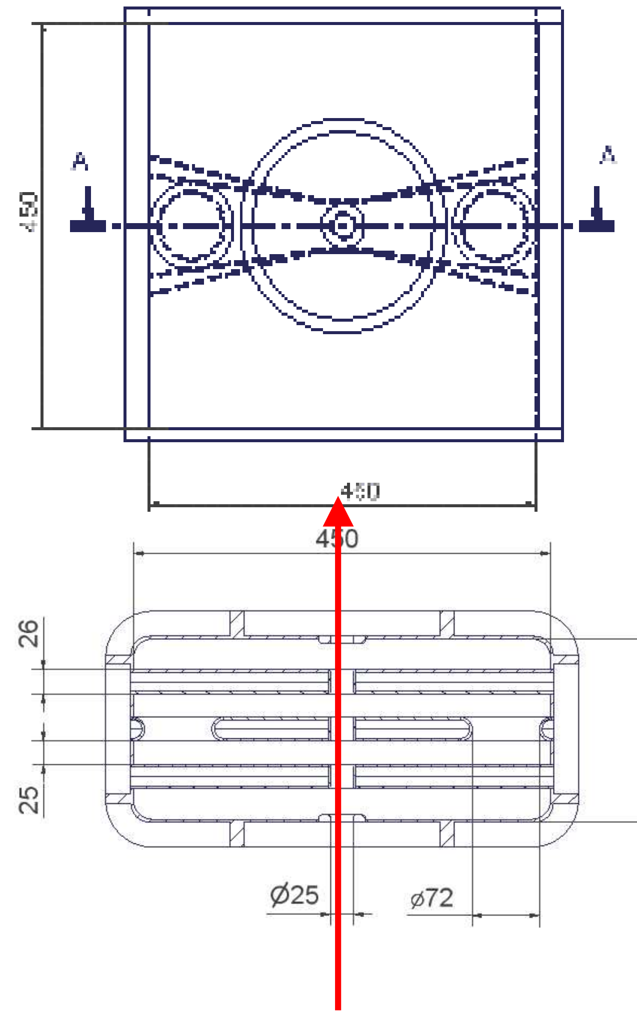
With respect to QP-doublet and Solenoid, easier matching with the RFQ

The 4-gap Ladder Resonator



Huge flanged ports for:

- Inspections
- Repair (grinding and EBW)
- BCP and rinsing



Three stems (four gaps)

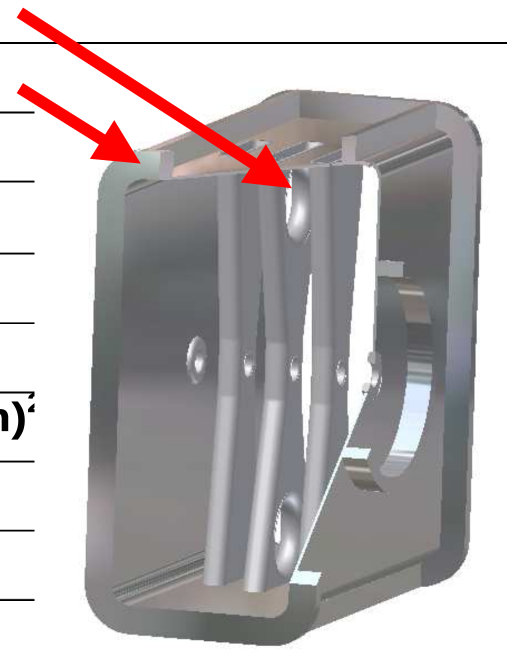
Stems have a racetrack cross-section

- from 65 mm to 125 mm (1st and 3rd)
- from 65 mm to 166 mm (2nd), with two 72 mmØ coupling holes

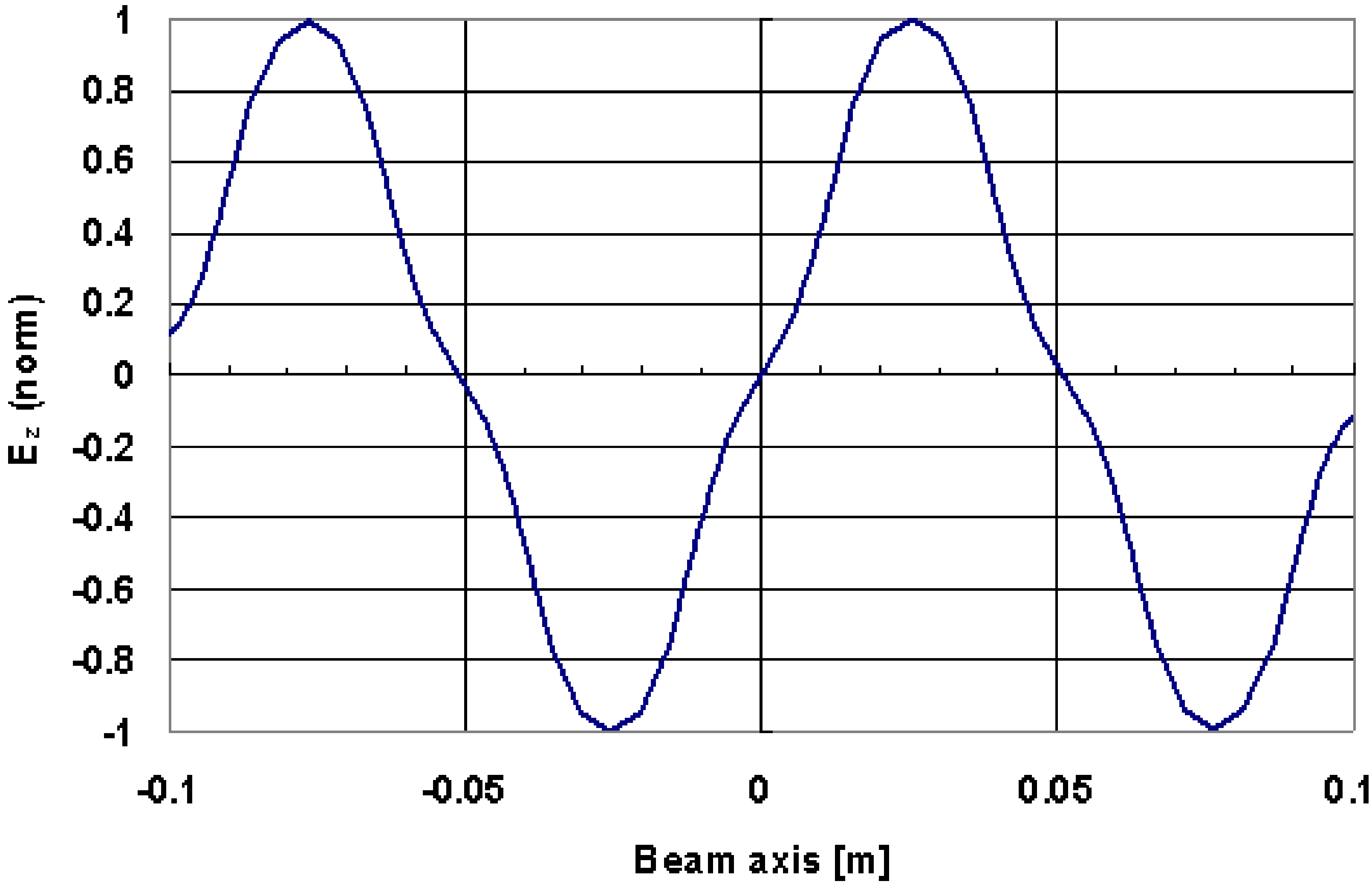
Beam bore 25 mm, Gap length 25 mm

Ladder Resonator (β_0=0.12): rf parameters

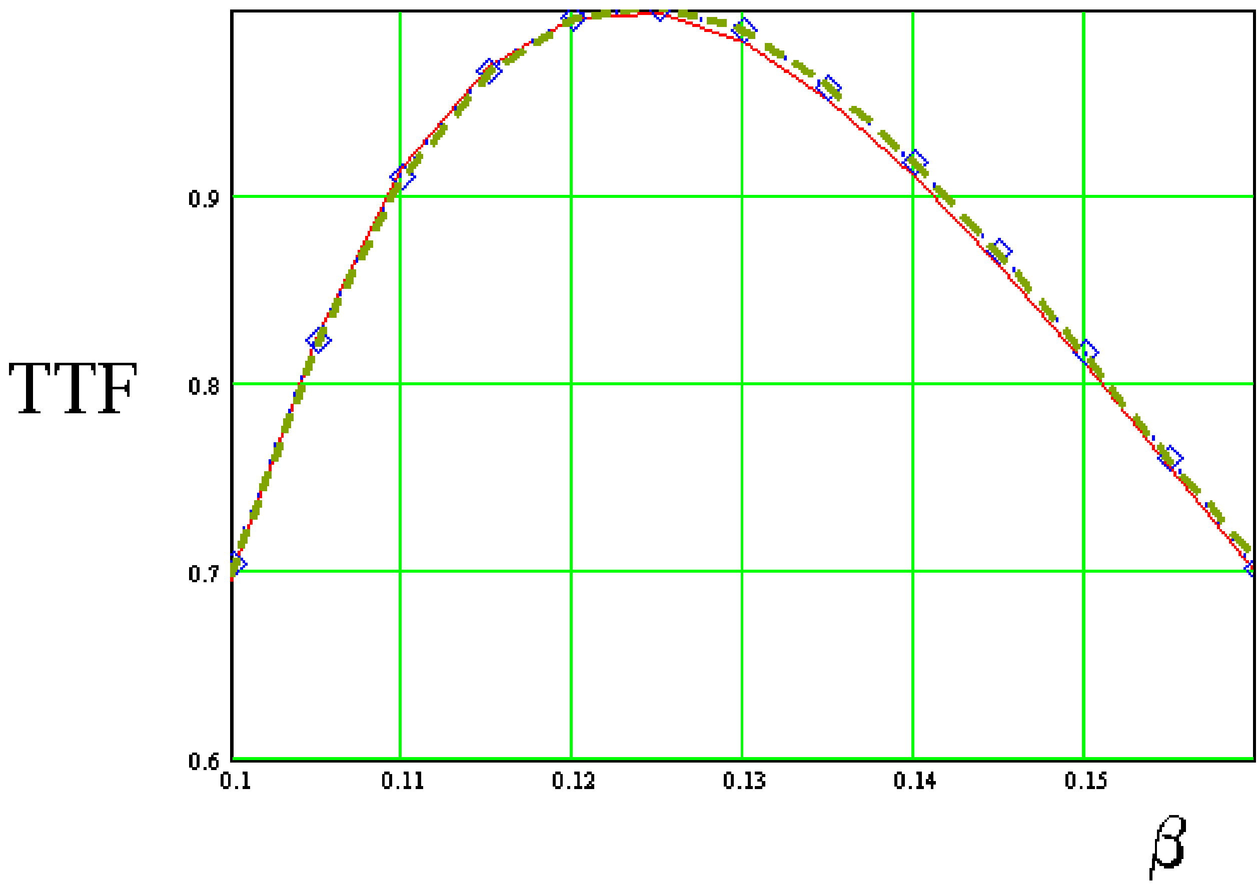
Frequency	352 MHz
Accelerating field flatness (between central and end cells)	100 %
$B_{s,p}$	65 mT (set as limit) @ the coupling hole
B at the flanged joint	1.5 mT
$E_{s,p}$	20 MV/m
Energy gain at β_0 = 0.12	1.15 MeV/q
Accelerating Field E_0	5.8 MV/m
Beam Loading	4.2÷5.8 kW
U/E_a^2	59 mJ/(MV/m)^2
Rf coupling (coupling holes)	1.2 %
Q - @ 4 K (assumed)	5 x 10^8
Geometrical factor G (Ω)	45 Ω
$B_{s,p}/E_0T$	11.2 mT/MV/m
P_{diss} (@ Q = 5 x 10^8)	10 W



Field Uniformity on Beam Axis = 100%

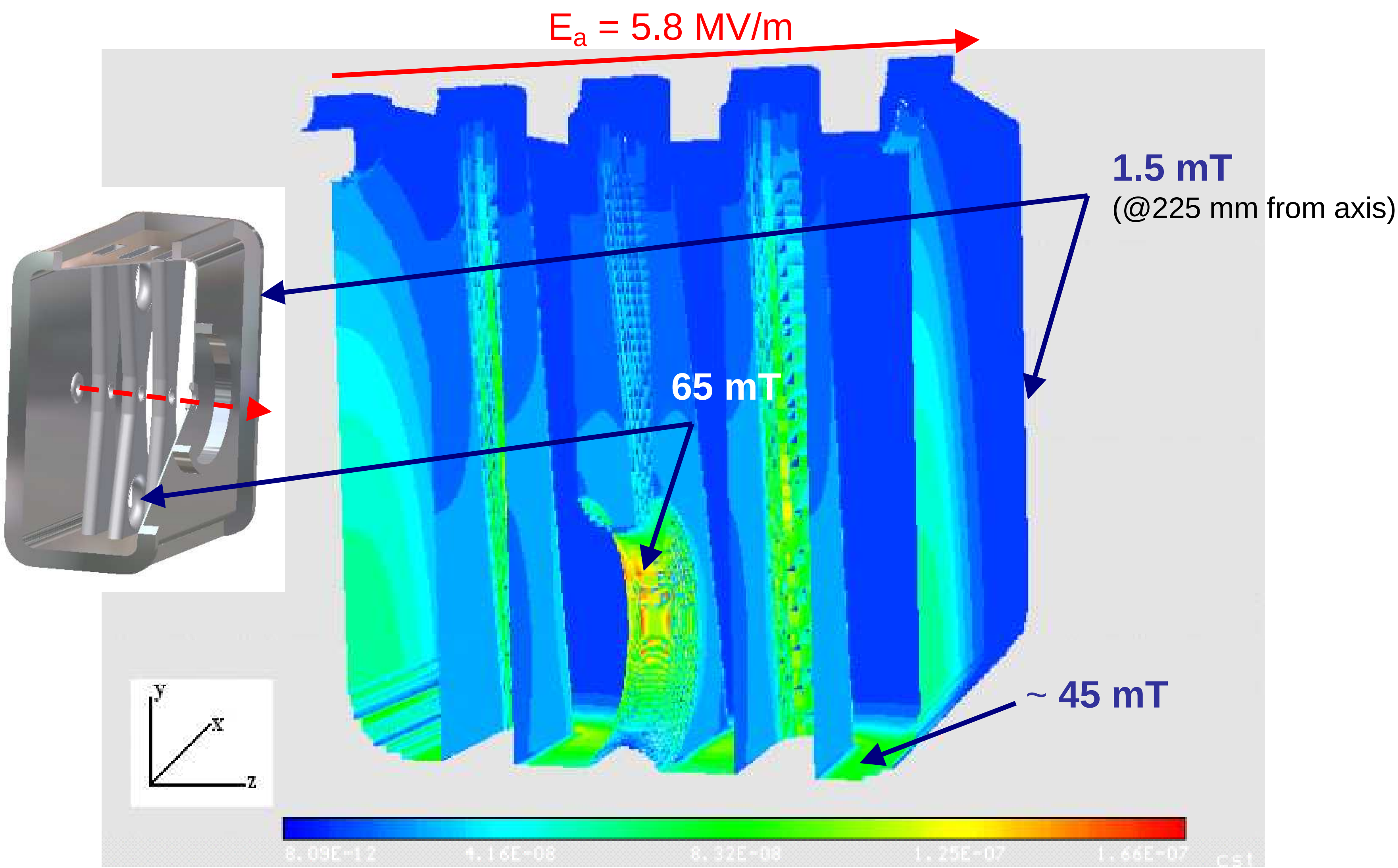


β_0 = 0.12 Ladder: TTF curve

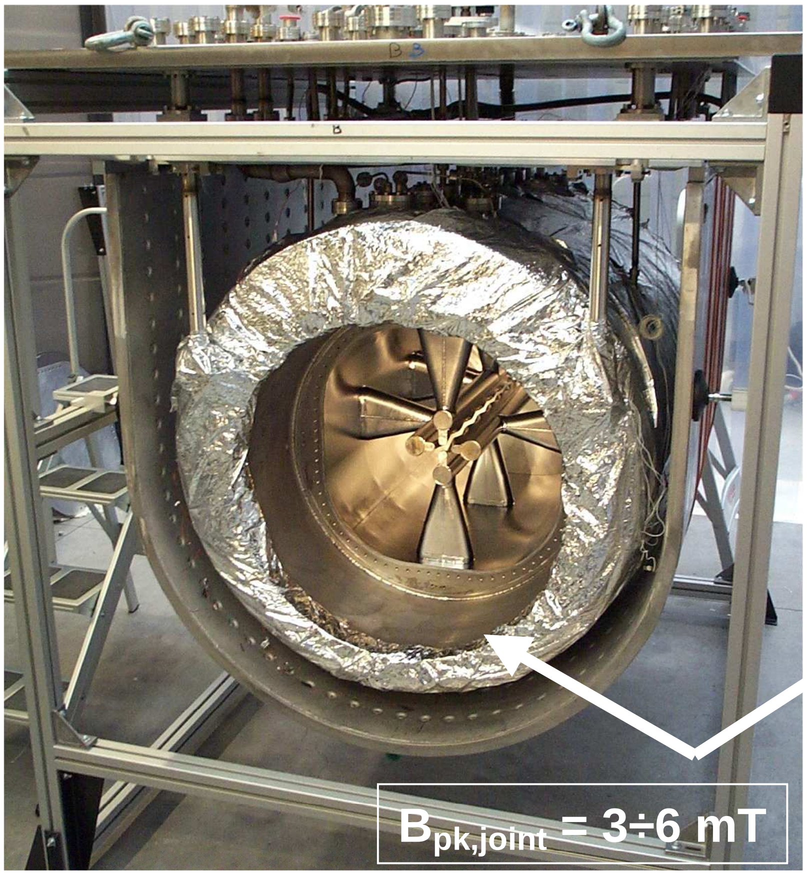


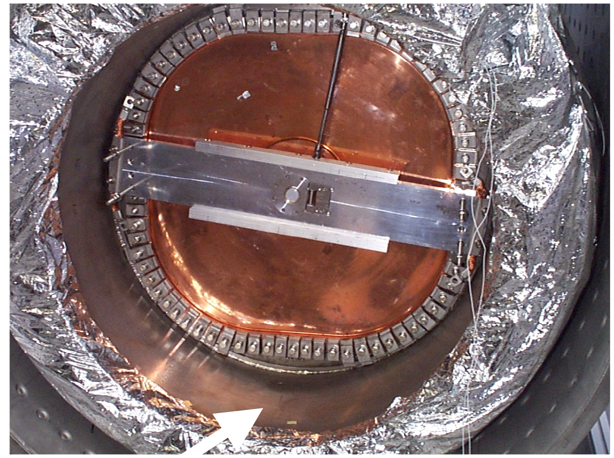
TTF curve of the ladder resonator (blue diamonds),
plotted together with the polynomial approximation (eq. (1), green dash curve)
and the 4-thin-gap approximation (eq (2), red solid curve).

Distribution of Surface Magnetic Field

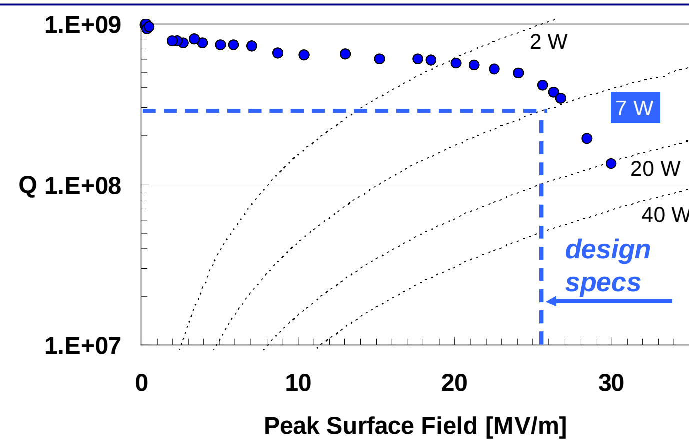


SC Joint on SC-RFQ at INFN-LNL

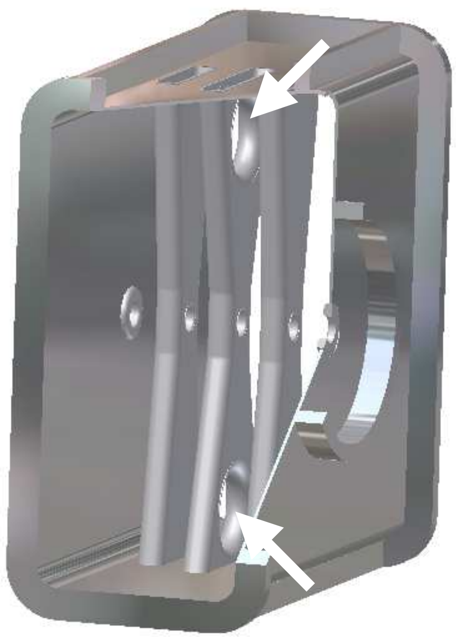


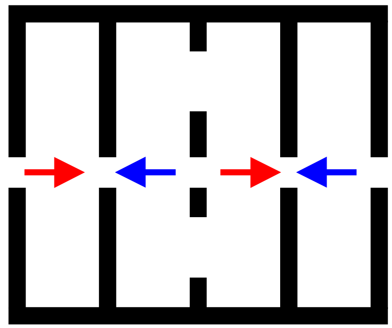


Nb/Cu sputtered end-plate (no gasket, just pressure – **see also** **K.W. Shepard, IEEE Trans. on Nucl. Sci., NS-24, N.3, June 1977, 1147**

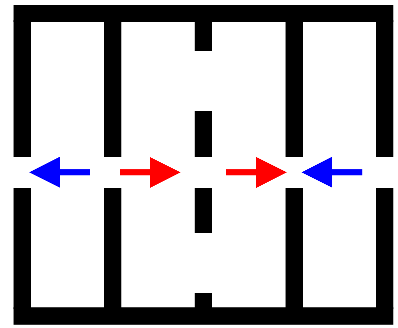


RF Coupling

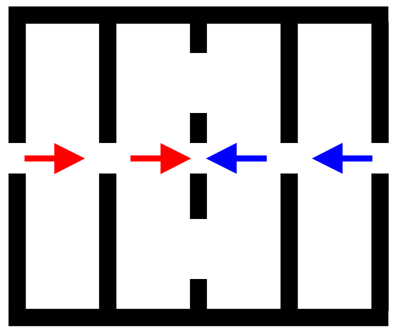




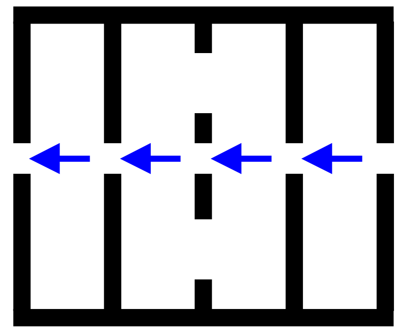
f_0 = 352 MHz (w.m.)



f_1 = 356.3 MHz



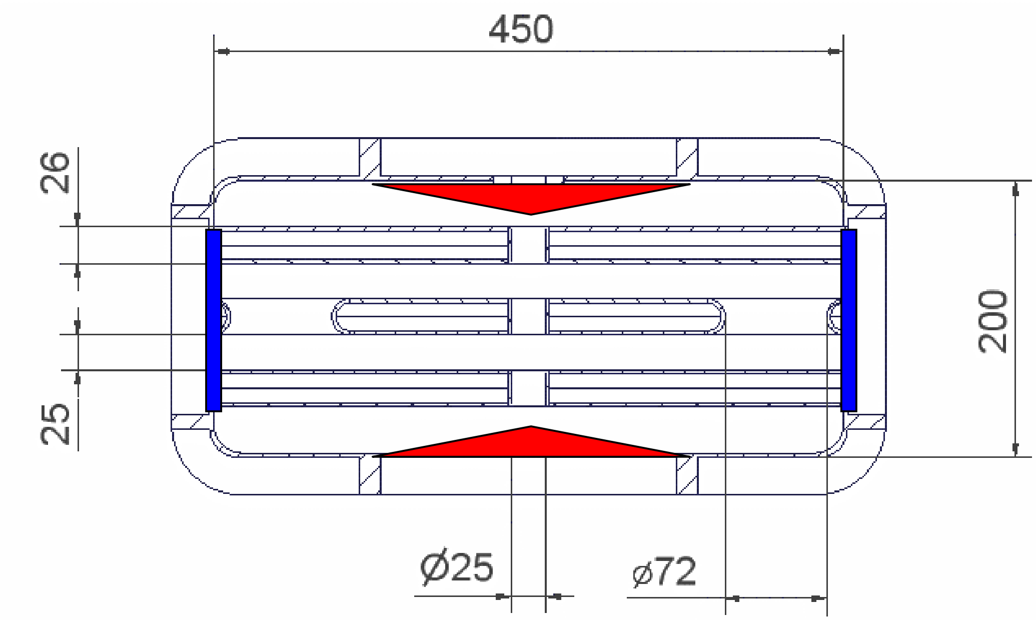
f_2 = 357.2 MHz



f_3 = 449.1 MHz

Without coulping holes:
Gap length very small vs. stem width → mode degen.
With holes: 1.2 % coupling
Positioning error of one stem by 0.1 mm in z → 1% deviation in E_z flatness (and mode separation +1.5%)

Frequency Tuning



Rough Tuning (**during construction**): stepwise reduction of stem length (both sides)
+1.33 MHz/mm

Fine Tuning (**in operation**): end-plate deformation (both sides)
-1.08 MHz/ (0.1mm)

Outlook

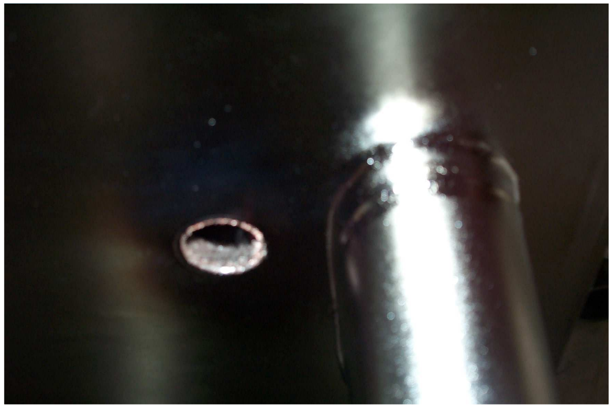
- **Compact acceleration** of a **5 mA** p beam (12 cavities, 2 cryostats, 7 m): **5÷20 MeV (β = 0.1÷0.2)**

- The Ladder scheme allows **ample access** for **inspection, repairs and treatments** while retaining **good rf properties**

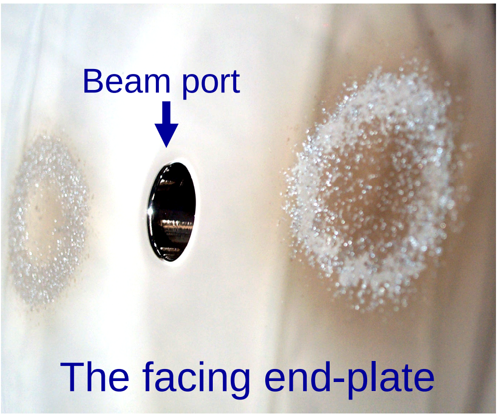
  (100% field flatness, E_{pk}=20 MV/m, H_{pk} = 65 mT, E_a = 5.8 MV/m)

- Mode degeneration is overcome by **rf coupling holes** in the central stem

- **Next steps**: **mechanical analysis**, EBW and **construction tests**, definition of **tuners** and **rf ports**, design of the **liquid He dewar**

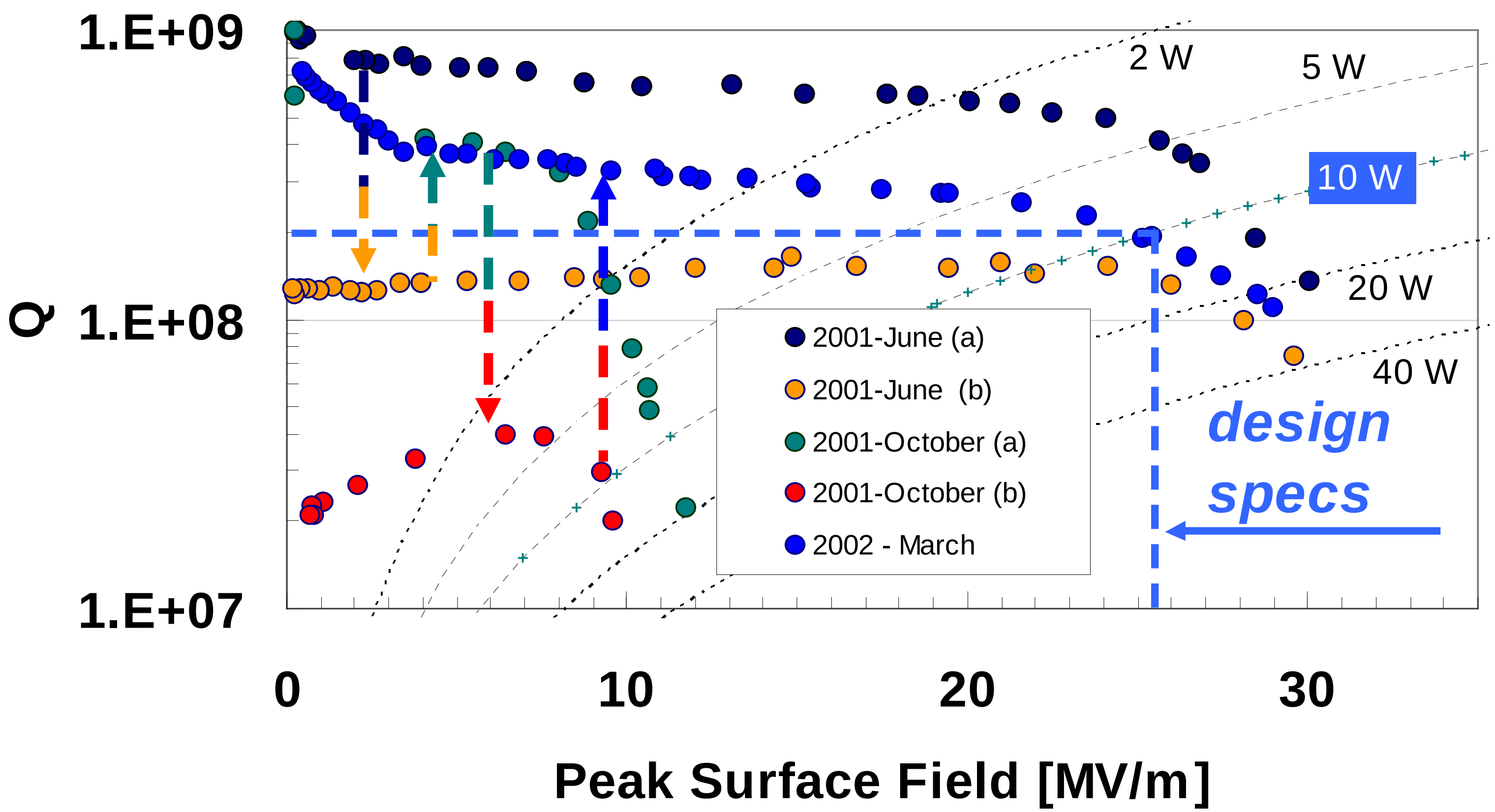


- Plasma discharge: sputtering of Cu and INOX layer in a high-j region
- Chemical Polishing would have taken months
- **No CP**, 3M – Scotch Brite **lapping followed by HPWR** (2 weeks)

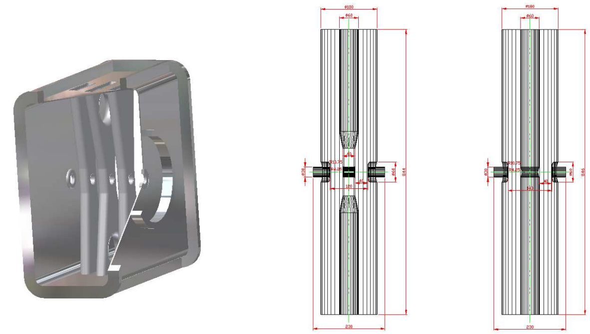


- **CP** again **avoided**
- 3M – Imperial**,**
  with Al_2O_3 abrasive (60 to 2 μm)
- **HPWR**

Evolution of SRFQ2 Performance



Superconducting cavities



Cavity type	4-gap	4-gap	HWR	HWR	units
β_0	0.124	0.17	0.25	0.33	
n. of gap	4	4	2	2	
E_p/ E_a	**~3.**	**~3.**	**~4**	**~4**	
H_p/E_a	**102**	**100**	**95**	**106**	**Gauss/(MV/m)**
$R_s \times Q$	45	62	54	66	Ω
Eff. length	0.2	0.29	0.18	0.214	m
Bore diameter	25	25	30	30	mm
Design E_a	6	6	6	6	MV/m
Design energy gain	**1.2**	**1.74**	**1.08**	**1.284**	**MeV/q**
n. required	6	6	32	32	

Linac compactness at low β

Δ**W**: maximum acceleration/cavity is desired for economy reasons

Parametric resonance σ_L=2σ_T must be avoided (<u>width</u>: 0.4" σ_T/σ_L" 0.6)
σ_T " π/2 (**envelope instability**)

Consequently: σ_L = σ_T/0.4 **= π/0.8.** But:

$$\sigma_L \approx L\sqrt{\frac{en\Delta W}{mc^2 L}\,\frac{2\pi\sin(-\phi_s)}{\beta^3\gamma^3\lambda}} \propto \sqrt{L}$$

(E average accelerating field, n number of cavities per period, β – γ relativistic parameters, λ rf wavelength)

Given cavity no. and energy gain, there is a limit on the period length **L**

A **compact lattice** is needed **for high performance cavities**

Linac lattice

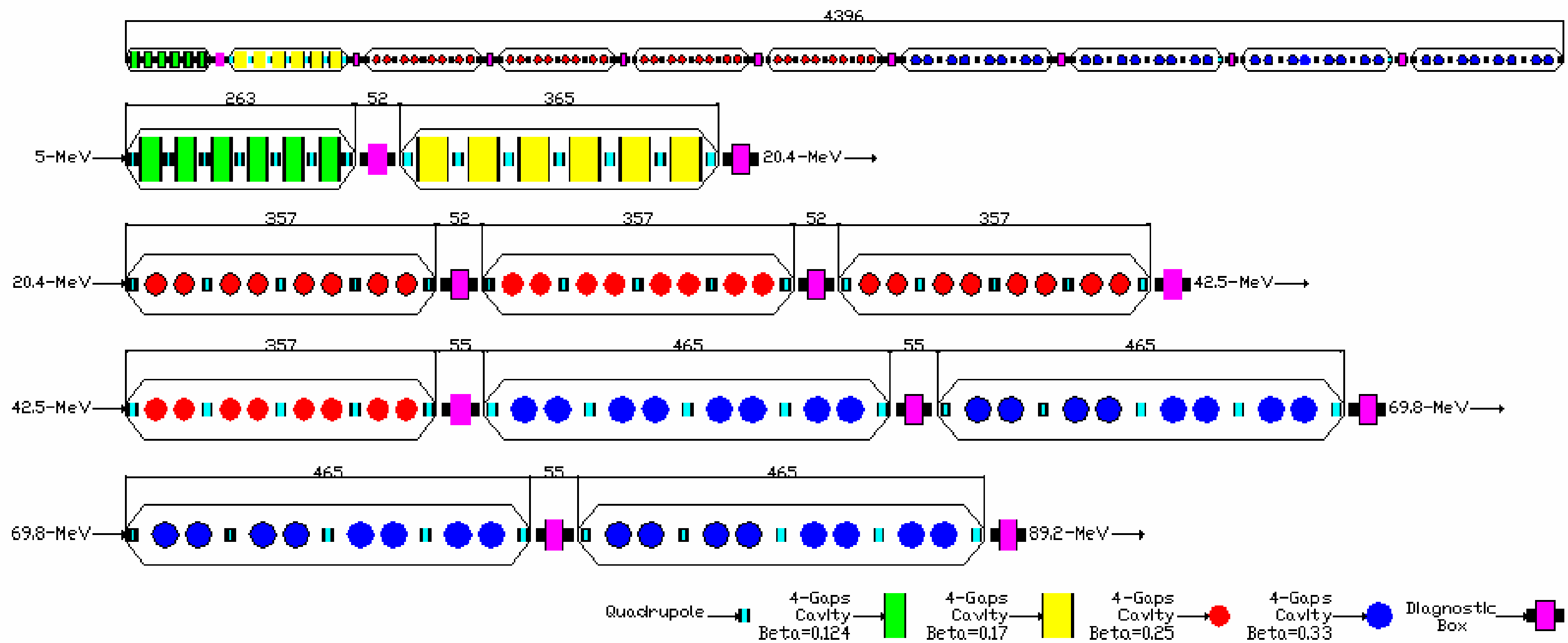
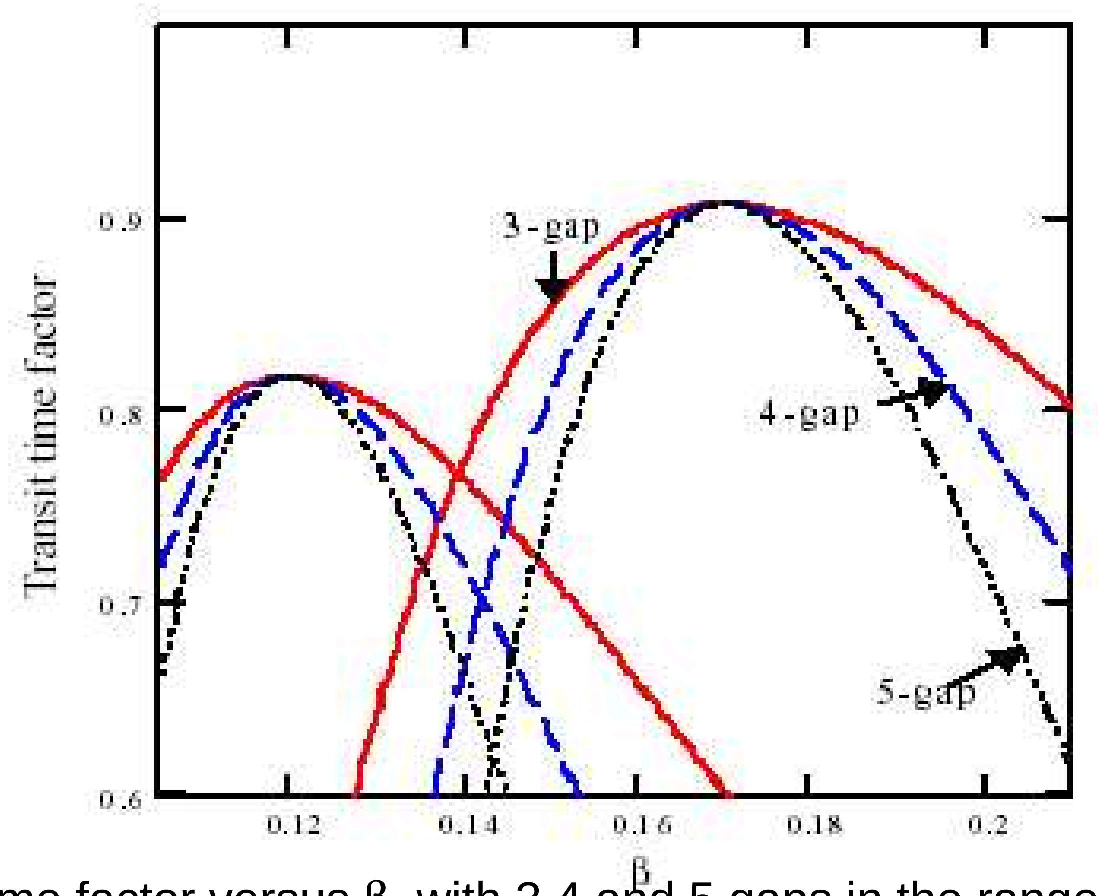


Figure 1 *Linac layout*

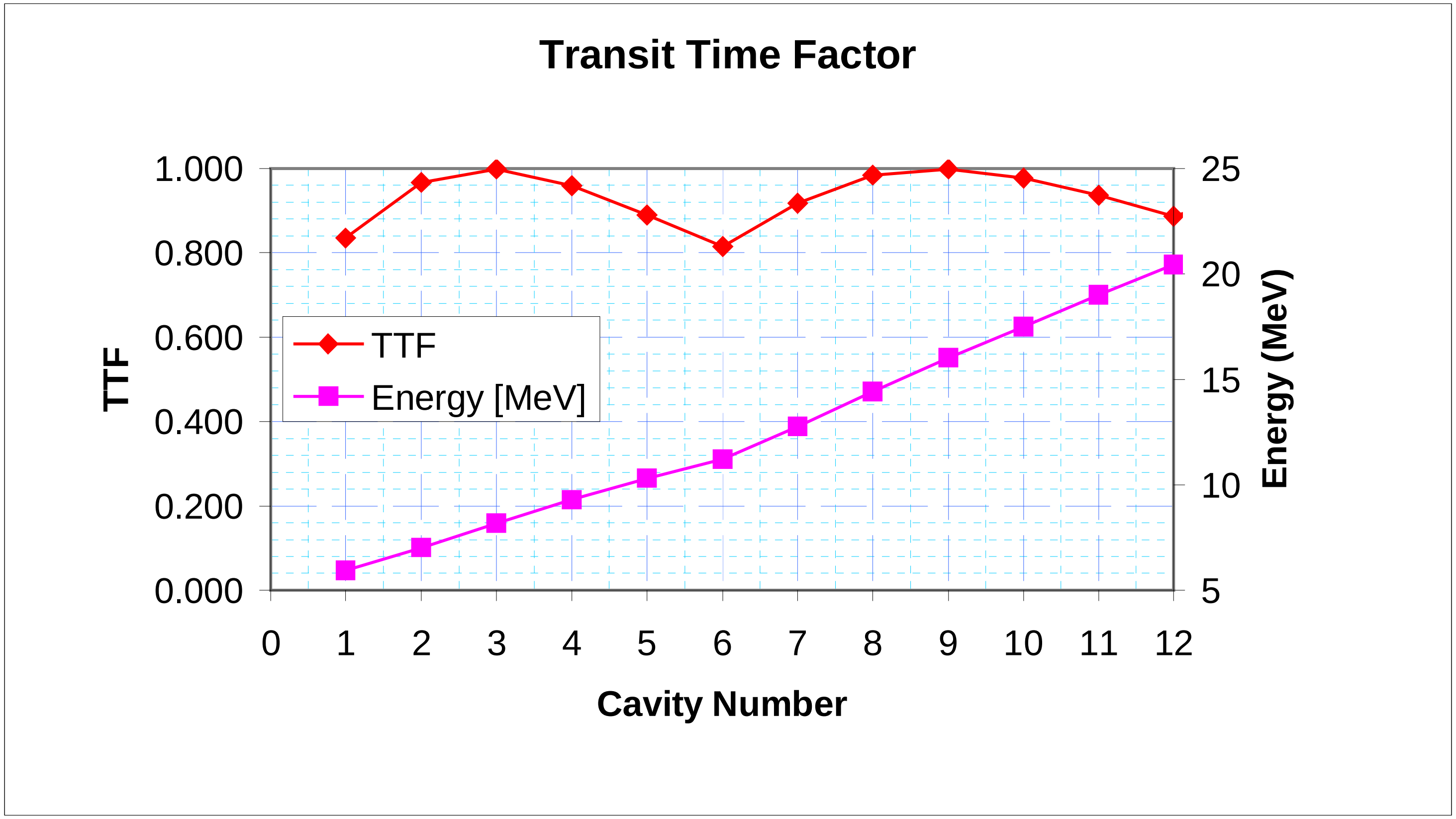
Length = 44 m, 10 cryostats, 76 resonators, E_{fin} = 90 MeV

Choice of the number of gaps in the desired beta range



Transit time factor versus β, with 3,4 and 5 gaps in the range b = 0.1÷0.2

TTF and Energy along the linac



(TTF is calculated here for ideal gaps, with $\beta_0 = 0.12$ and $\beta_0 = 0.17$)

4-gap Ladder Resonator (β_0=0.17)

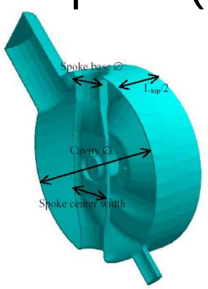
Frequency	352 MHz
Accelerating field flatness (between central and end cells)	96 %
$B_{s,p}$	65 mT (set as limit) @ the coupling hole
B at the flanged joint	1.5 mT
$E_{s,p}$	25 MV/m (reas. limit 25÷30 MV/m)
Energy gain at β_0 = 0.12	1.68 MeV/q
Accelerating Field E_0	8 MV/m
Beam Loading	6÷8 kW
U/E_a^2	89 mJ/(MV/m)^2
Rf coupling (coupling holes)	0.7 %
Q - @ 4 K (assumed)	5 x 10^8
Geometrical factor G (Ω)	62 Ω
$B_{s,p}/E_0T$	8.7 mT/MV/m
Rf power dissipation (@ Q = 5 x 10^8)	10 W

Which cavity to squeeze in the available space (L_{int}=0.2 m)?

Common reference: H_{pk} < 65 mT, E_{pk} < 30 MV/m

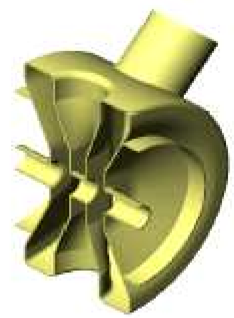
2-gap options

- HWR, QWR conical and cylindrical: E_{pk}/E_a ~5, ΔW < 0.6 MV
- Spoke (examples)



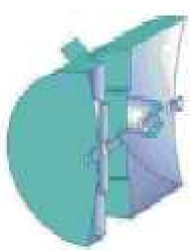
G. Olry et al., IPN-Orsay
EPAC2002, p. 2691

352 MHζ, β_0 **= 0.19**
E_{pk}/E_a = 3.56
E_a = 8.4 MV/m



DESIGN OF A β=0.175 **2-GAP SPOKE RESONATOR***
F.L.Krawczyk et al., SRF2001
http://conference.kek.jp/SRF2001/

3-gap options



K.W. Shepard et al., ANL
SRF2001
345 MHz, β_0 = 0.39

V. Andreev et al., INFN-LNL
EPAC2002, p. 2208

352 MHz, β_0 **= 0.13**
E_{pk}/E_a = 4.65
Ea = 4.77 MV/m

Discussion on "The Ladder Spoke Resonator at INFN Legnaro" by Giovanni Bisoffi

Bisoffi presented the results of the design work for a box-shaped 3-spoke resonator with a ladder arrangement of spokes. Due to the presence of flat walls he was asked about potential multipacting in this type of structure. Bisoffi said that no simulations have been done so far. But he pointed out that this cavity topologically is similar to the Legnaro superconducting RFQ that showed low level multipacting, which could easily be processed during start-up.

He also confirmed their plan to have huge demountable side walls that allow good access for cleaning the inside of the cavity.

Delayen asked about the relation of the field flatness inside the cavity and the fact that all gaps are of equal length. Bisoffi explained that the field flatness is set by the shape of the taper on each individual spoke. Delayen pointed out that this only works due to a weak cell-to-cell coupling, similar to that in elliptical cavities. Structures with strong coupling require halfcells at the ends. The effect of the individually shaped spokes means that the endcells and the midcells have different frequencies. This means strong variation of the field flatness with endcell tuning.

Pagani stated that implementation of structures is of lesser importance. In the end voltage gain, transit time factor and peak fields are what counts. Bisoffi confirmed that except for the shunt impedance all RF-parameters are in line with other designs. The main motivation for investigating the ladder structure is the potential to have better access to the cavity interior for cleaning.

General Discussion on RF-design led by Ken Shepard and Jean Delayen

The general discussion session continued with details of the ladder design. Shepard pointed out that these spoke resonator designs always have to do a trade-off between making the structure ”floppy” for tunability and making it stiff enough so that microphonics e.g. due to variations in the helium bath pressure do not become a major issue. He asked if for the boxy ladder structure these issues have been studied, as this geometry is more susceptible to pressure variations. Bisoffi answered that mechanical studies have just begun and did not go beyond the basic mechanical modes of the structure, yet.

Schrage asked about the cost issues due to the use of the huge niobium flanges as the sidewalls that allow access to the interior of the cavity. Bisoffi answered that similarly sized flanges have been used for their superconducting RFQ. They worked well and were reasonably priced. Some cost and complexity reduction comes from the use of a combination of niobium and titanium. Titanium is used for parts of the flange that do not carry any RF current.

Zaplatin stated that from his comparisons between ladder and cross-bar structures the cross-bars were superior in terms of peak surface fields for low-β structures. For higher-β structures that have a larger volume these structures could be a more interesting option. He thinks that their major benefit is the potential to better clean the inside due to the large sidewall port. This should increase the achievable gradient in these structures. He also mentioned that the locations of flat surfaces that tend to deform more due to helium pressure changes are in lower field areas that should have less effect on the frequency changes in the cavity.

Addressing the fine tuning of resonator geometries to lower peak fields and thus increase achievable gradients, Rusnak asked if anybody ever considered non-symmetric gaps in multigap resonators, making the first one shortest and gradually increase succeeding ones. He was curious if an increase in transit time factor could be expected. Shepard pointed out that these structures are anyhow used over a wider energy range and thus internal tweaking should have little additional benefit. Rusnak pointed out that there still might be an effect as particles are faster after each gap thus making larger gaps later inside a structure better matched to the particle velocity. Bisoffi added that this non-symmetric design could be used to lower the peak fields in the endcells and thus allow a higher gradient than a constant structure.

Delayen made some comments on the general design procedure for 2-gap spoke resonators. His experience showed that gapcenter-to-gapcenter distances of $\beta\lambda/2.2$ gave the lowest peak surface fields, if the design procedure adjusted the overall active length of the resonator to maintain this distance, even when the spoke thickness is modified. For this approach he always found optimum solutions, where the spoke thickness consumed half of the active cavity length. As an additional argument for this approach he reminded us that besides the frequency, the structure-β is the most important RF-structure parameter provided by the beam-dynamics and that this parameter should be maintained. Pagani commented that the important feature for the beam-dynamics simulations are the actual fields and their oscillations. In this scheme the definition of β is purely arbitrary. He agreed however that the definition of β needs to be consistent among designs. He also pointed out that the definition of β should be tied to the length of a accelerating structure. He added furthermore that the ”β-label” of a transit time factor curve is meaningless as these curves are also influenced by other quantities, like the aperture and length of a structure.

Shepard made a few more remarks on the proper comparison of structures. He mentioned that in the end the performance of a structure counts and that probably the peak surface fields for a specific voltage gain are useful numbers to compare. He also suggested to resolve the discrepancy between his and Delayen’s optimal spoke thickness of $L_{cav}/2$ compared with the Orsay result of $L_{cav}/3$.

The discussion on optimization strategies next focused on the quantities that were kept invariable during a design. There was a general agreement of the fixing of the β for any optimization. Pagani then pointed out that also the optimization criteria for a structure vary. While in Europe generally peak magnetic fields of 50 mT are seen as a fixed upper field level criterium, a lot of US-designs focus more on the peak electric field. Here the recent SNS number of 27.5 MV/m is becoming a standard for the upper limit for achievable field levels. For these designs sometimes peak magnetic fields of 60 mT or more would be reached. These criteria add more obstacles to comparing structures.

Shepard responded that a constant maximum peak surface field independent of the structure is not sufficient. He believes that from a better understanding of the mechanism behind field emission a peak surface field criterium should include the surface area of the structure. He asked for volunteers to collect and interpret the data for this information to get better peak surface field criteria for different structures. He agreed to Pagani’s remark that better HPR reduced the importance of field emission to a certain degree.

Krawczyk started a discussion on the ports attached to the spoke resonators. Orsay and LANL are the only designs that use huge coupler ports due to the potential requirement of accelerating beam currents in the range of 100 mA. He asked if the much smaller ports on other designs are matched to the expected beam current operation of their accelerators or if they are solely for prototyping purposes. Shepard answered that the ports on RIA are matched to the expected operation. They have a preliminary coupler design whose thermal management for the nominal operation with 2 kW of transmitted power and also for up to 20 kW of overcoupled operation for microphonics compensation is reasonably well understood.

Mechanical Designs

Tom Schultheiss: "*Gusset Design and Analysis of the RIA Two Spoke Cavity*"
(Abstract | Viewgraphs | Discussion)

Guillaume Olry: "*CNRS: XADS/Eurisol*"
(Abstract | Viewgraphs | Discussion)

Dale Schrage: "*Mechanical Design of the AAA Beta=0.175 Spoke Resonator*"
(Abstract | Viewgraphs | Discussion)

Gusset Design and Analysis of the RIA Two Spoke Cavity *

T.J. Schultheiss, J.W. Rathke,
Advanced Energy Systems
K. Shepard, J. Fuerst, M. Kelley
Physics Division Argonne National Laboratory

The Two Spoke Cavity for the Rare Isotope Accelerator (RIA) operates at 4 K in boiling helium. This operating mode produces pressure variations that affect the resonant RF frequency of the cavity. The design of the gusset includes shaping that attempts to cancel the effects in the magnetic field region with those in the electric field region. A mechanical tuner is also proposed that primarily produces frequency shift from the electric field. The goal of the design is to produce a significantly larger frequency shift with the mechanical tuner than results from pressure variations. The design requirements include room temperature stress limits and a 21 psi pressure differential.

* AES work supported by Argonne National Laboratory under Contract 1F-00761. ANL work supported by the Department of Energy.

Gusset Design and Analysis of the RIA Two Spoke Cavity

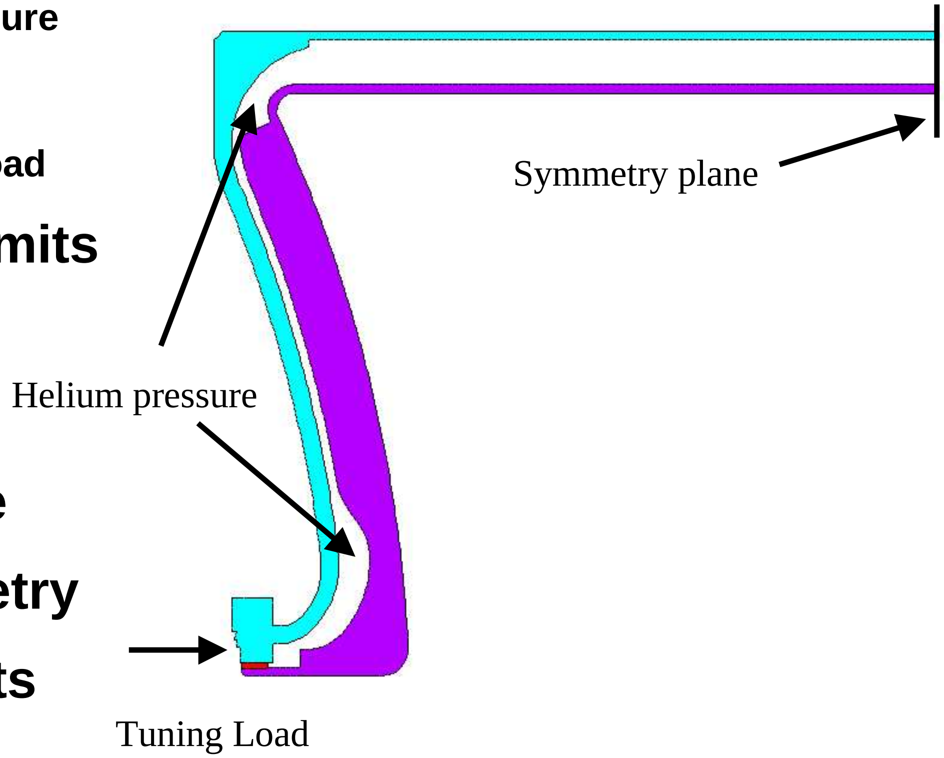
T. Schultheiss
Advanced Energy Systems

K. Shepard, M. Kelly
Argonne National Laboratory

10/7/02
Spoke Cavity Workshop Los Alamos National Lab

Purpose

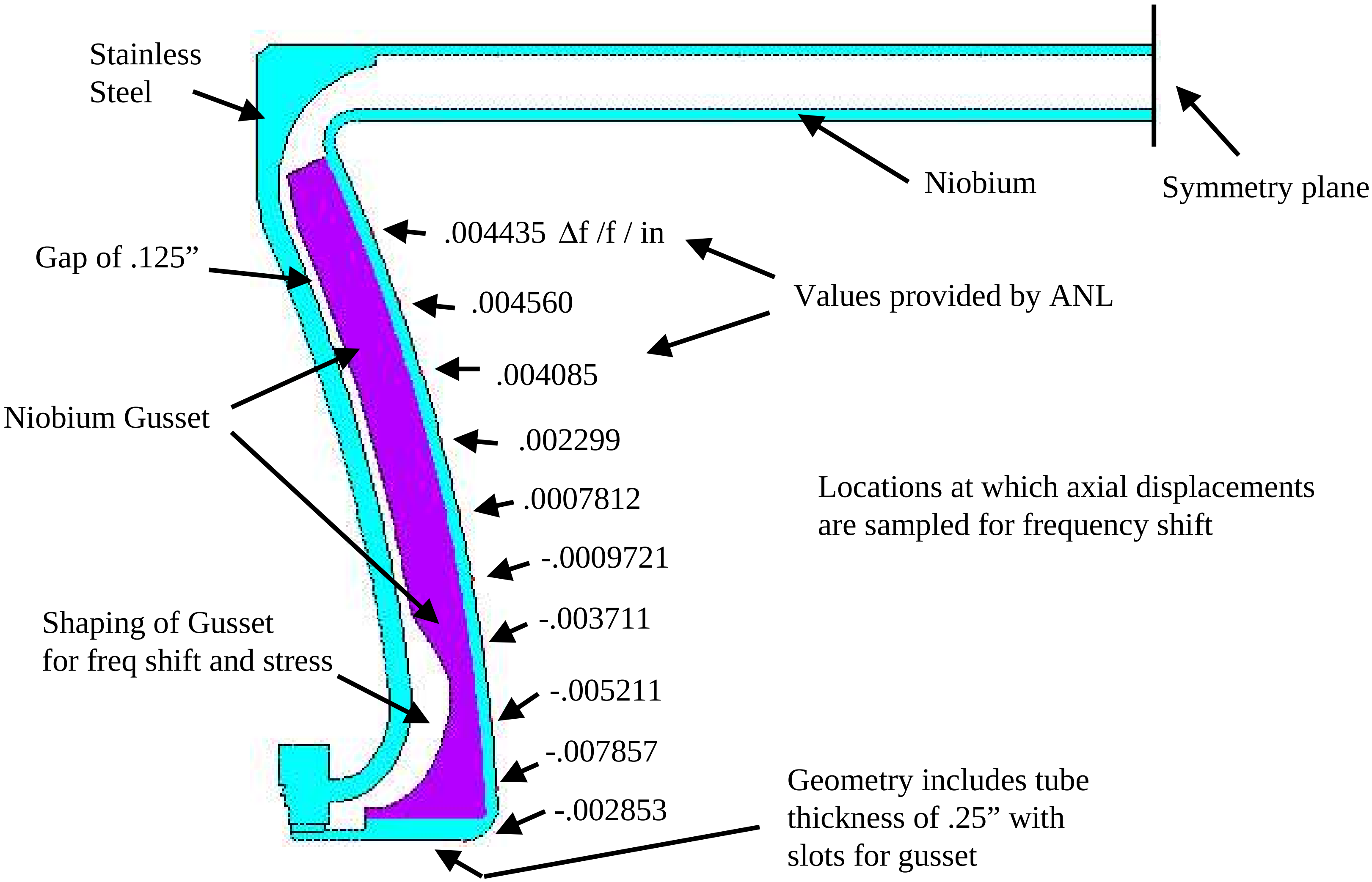
- **Gusset was shaped to minimize pressure induced frequency shift (K. Shepard)**
  - **Effects of system pressure**
    - **tolerance of helium bath pressure**
      - **18 psi ± 3 psi**
  - **Effects of mechanical tuner**
    - **frequency shift from a given load**
- **Room temperature stress limits**
  - **Helium pressure load**
  - **Tuning load**
  - **combined**
- **Minimize the helium volume**
- **2- D to define gusset geometry**
- **3- D to determine 3- D effects**



Advanced Energy Systems, Inc.

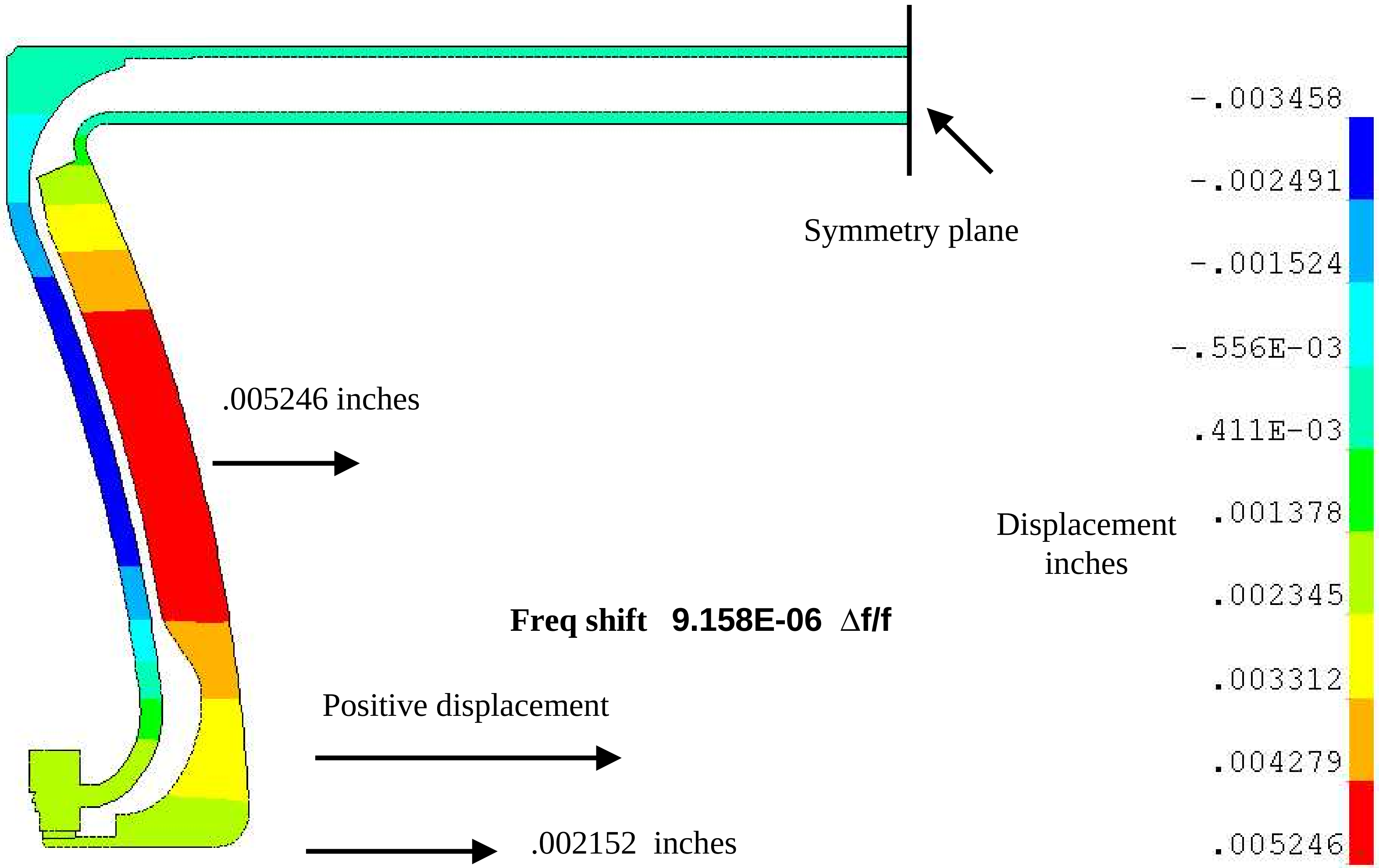
Gusset geometry and frequency shift sensitivity

- **Final Gusset geometry after many trials**



Displacements due to pressure load

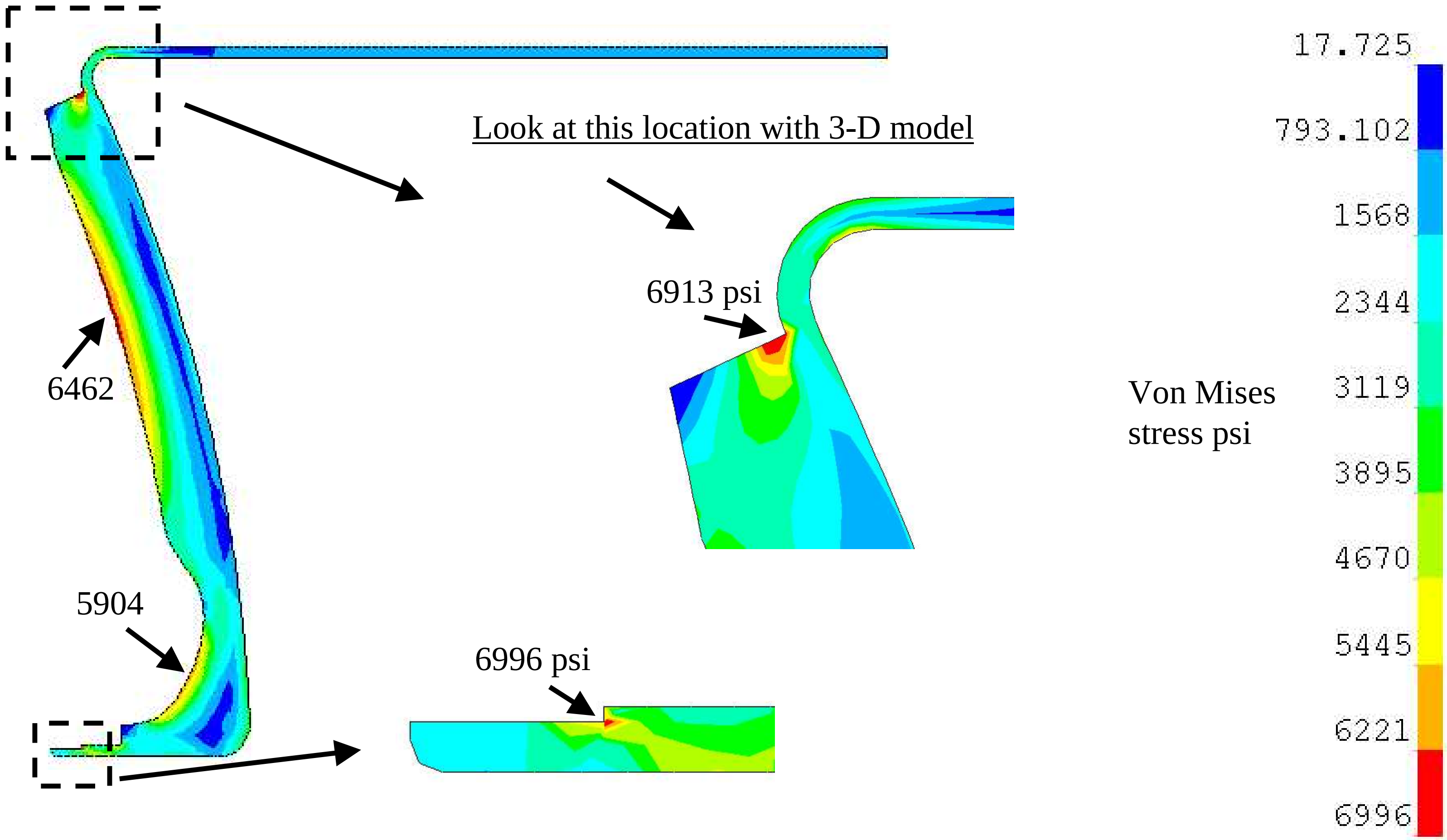
21 psi pressure load



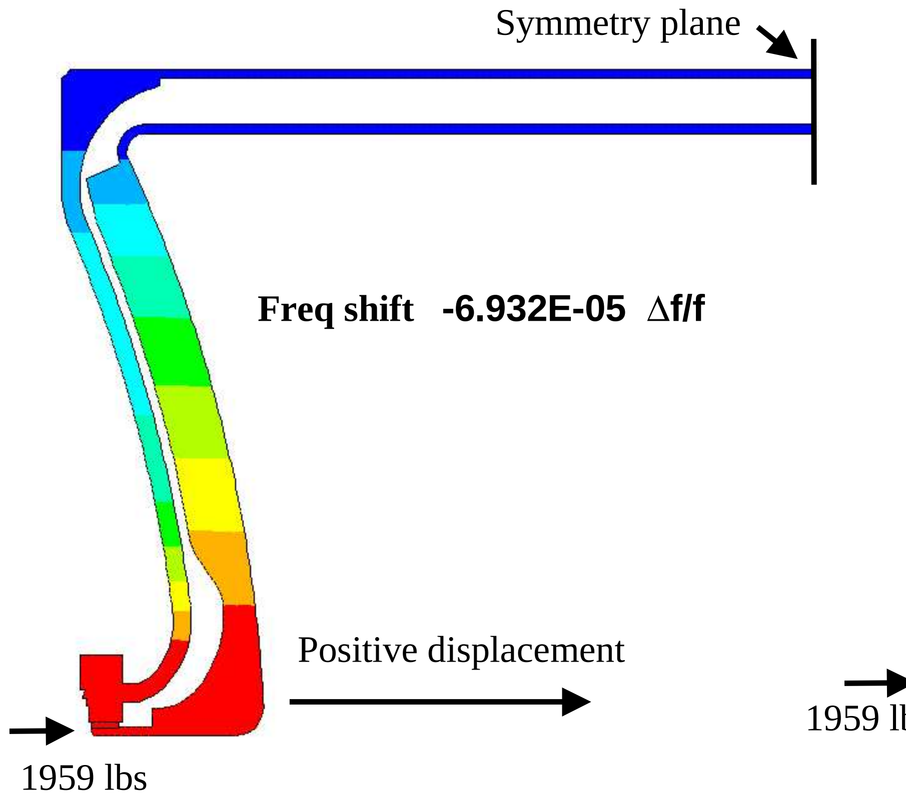
Freq shift 9.158E-06 Δf/f

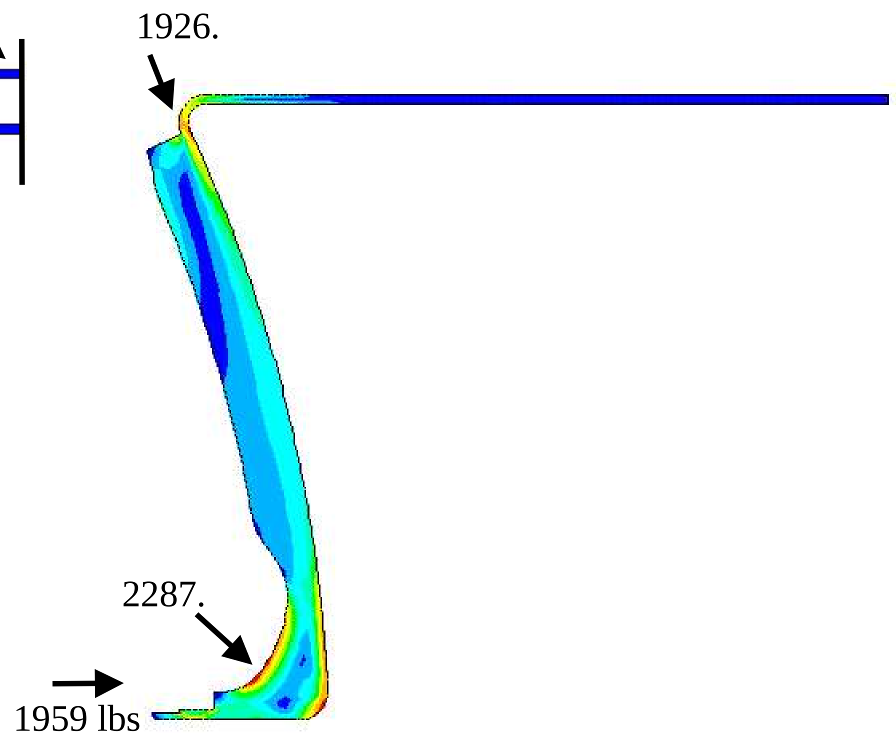
von Mises stress from pressure load

- **21 psi helium pressure**



Tuner force load results





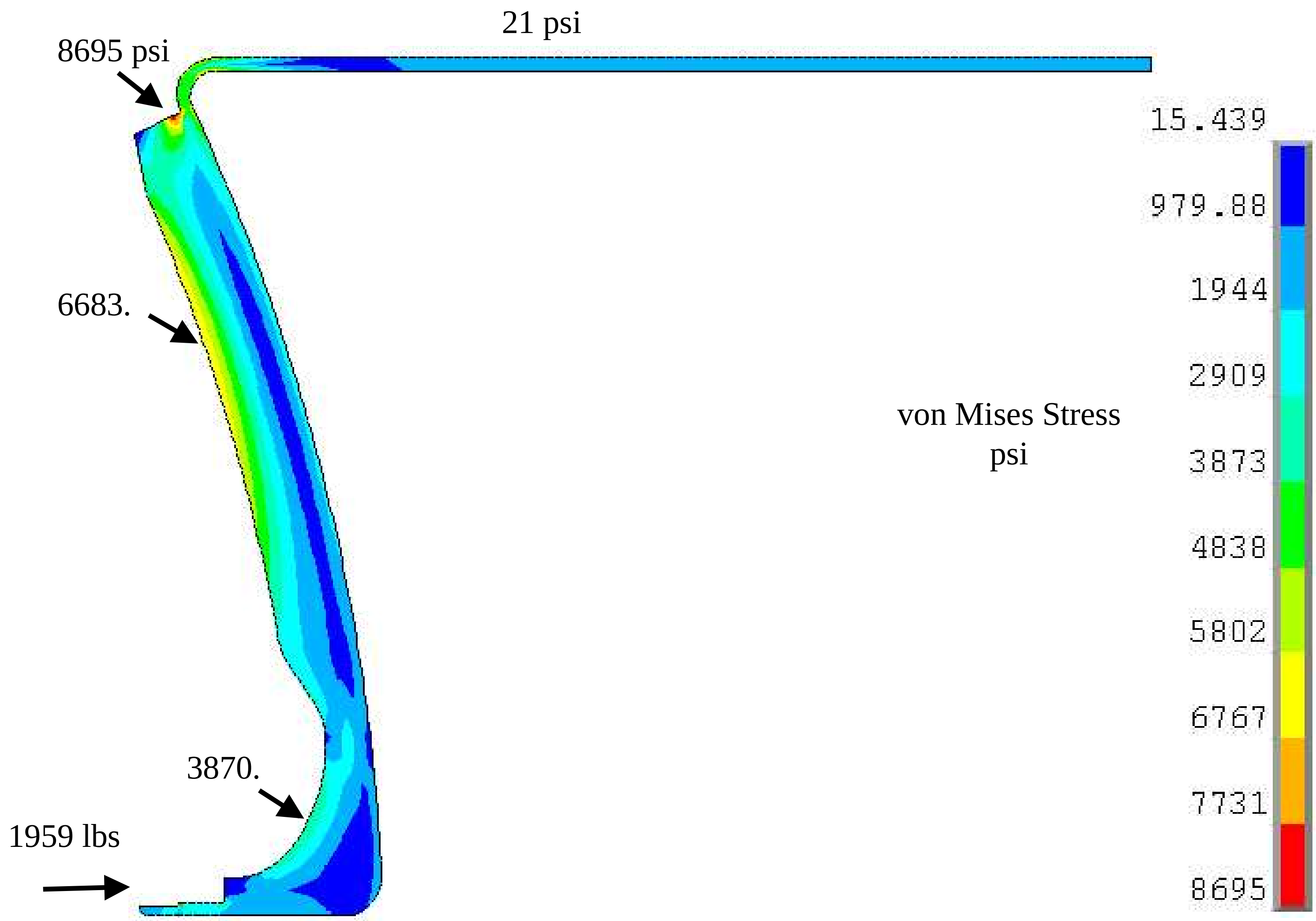
Displacement inches

.607e-3 .001857 .003107 .004358 .005608
-.187e-4 .001232 .002482 .003733 .004983

von Mises stress psi

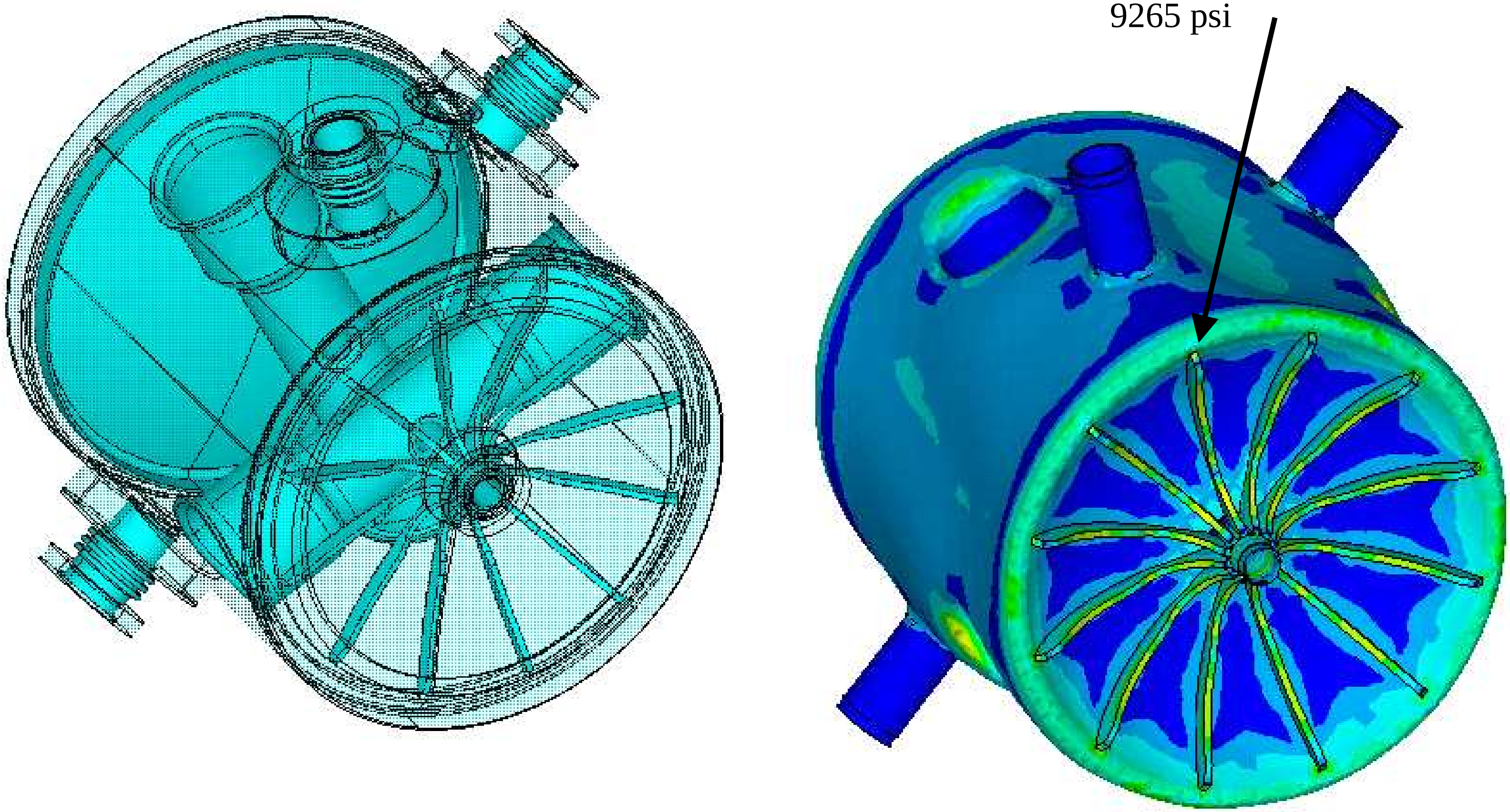
258.0 769.7 1281. 1793. 2305.
2.21 513.9 1026 1537. 2049.

von Mises stress pressure + tuner loads

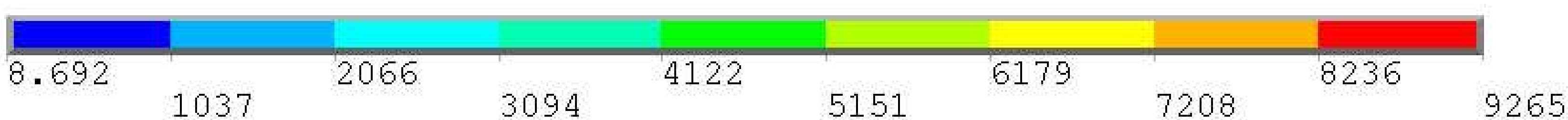


3-D model RT pressure stress results in niobium

Highest stress in model occurs here
9265 psi

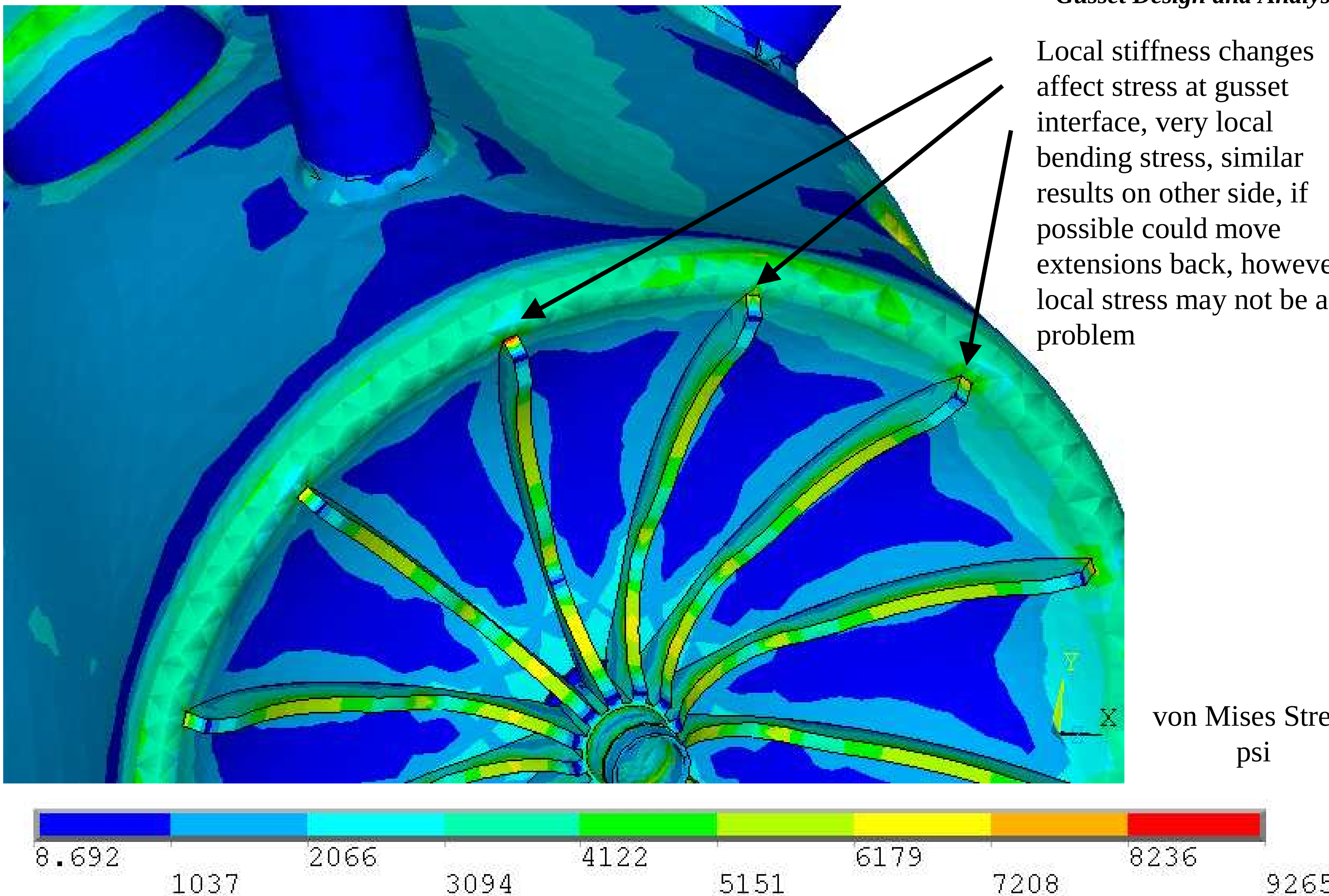


Von Mises Stress In Niobium PSI



Advanced Energy Systems, Inc.

RT pressure stress results in niobium



Local stiffness changes affect stress at gusset interface, very local bending stress, similar results on other side, if possible could move extensions back, however, local stress may not be a problem

von Mises Stress
psi

Tensile yield properties of niobium*^

Material	Room Temperature ksi	77 K ksi	4 K ksi
Niobium RRR 250	9.7	89.6	95.4
Niobium RRR 250 weld	10.2	64.5	68.2
Niobium RRR 40 (reactor grade)	11.0	64.2	67.9**
Niobium RRR 40 (reactor grade) weld	13.9	65.3**	47.4**

* From R. P. Walsh, et. al., "Low Temperature Tensile and Fracture Toughness Properties of SCRF Cavity Structural Materials", 9th Workshop on RF Superconductivity, paper tup014, Santa Fe, New Mexico, 1999.

^ Values are for 0.2% yield unless otherwise noted by **

** Failure occurs before 0.2% offset is reached

Conclusions

- **We have designed a Gusset stiffener to mitigate pressure induced RF frequency shifts**
- **Room temperature stresses are higher than we would have liked but are local and are not expected to result in an adverse effect on the overall structure**
- **Strength of Niobium significantly higher at 77K and below**
- **Using 12 1/4 inch thick flat gussets**
  - Frequency shift
    - **Pressure shift** **9.158E-06 $\Delta f/f$**
    - **Tuner shift** **-6.932E-05 $\Delta f/f$**
    - **Tuner/pressure shift ratio** **7.57 times**

Discussion on "Gusset Design and Analysis of the RIA Two Spoke Cavity" by Tom Schultheiss

The first question during the discussion was about the expected pressure change during cooldown. Shepard answered that people typically see around 1 atm, Kelley remarked that CEBAF as lowest value saw 1.8 atm. Shepard clarified that they are not using the CEBAF scheme, but, like in ATLAS use local heat exchangers. He expects around 21 psi pressure to be compensated.

On the question, if they worry about Q-disease and if they can cool down fast enough, if they use the heat exchangers he answered that this is not the limitation of their system. Schultheiss added that one has to keep in mind that for the cold system all allowables increase significantly so that no global yield problems are expected.

Shepard admitted that the localized stress in the gusset might have to be re-investigated if the system were to be produced today. He expects that the stresses can be further reduced, if needed.

Asked about the integrated design with helium vessel, Shepard explained that for some of their spokes, even with heavily reinforced end dishes, they saw significant detuning due to the external pressure. This was their motivation to look into the integrated, self-compensation design of cavity and vessel. With this setup they expect much less stiffening and much less susceptibility to microphonics effects. Compared to the significance of this improvement the localized stress in the gusset is seen as a secondary problem.

Zaplatin asked about the significance of the temperature in the tuning change simulations. Schultheiss and Shepard pointed out that the effect is purely local and df/f is changed insignificantly if you look at a cold or a warm start geometry.

XADS/Eurisol

G. Olry, CNRS, IPN Orsay

First mechanical studies on the β_g=0.35 spoke cavity have been performed to determine the niobium sheets thickness and the stiffeners shape and number we needed under vacuum load conditions. Additional calculations on tuning sensitivity (i.e. cavity stiffness) and mechanical vibration modes have been made.

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

IN2P3
INSTITUT NATIONAL DE PHYSIQUE NUCLEAIRE ET DE PHYSIQUE DES PARTICULES

Université de Paris-Sud

Mechanical study of “AMANDA”

IPN Orsay
Division Accélérateurs

Guillaume OLRY

Institut de Physique Nucléaire

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Introduction

Material properties of Niobium (RRR~250)

- Density: 8.57 $g.m^{-3}$
- Young's Modulus: 107 GPa
- Poisson's ratio: 0.394
- Yield strength : ~70 MPa @ 300K
- Tensile strength : ~150 MPa @ 300K

Calculations performed with ACORD-CP

- Yield strength limit: 50 MPa
- Only linear ➔ Von Mises stress values > 70 MPa are wrong !

Under vacuum load @ 1 bar

Cavity without stiffeners

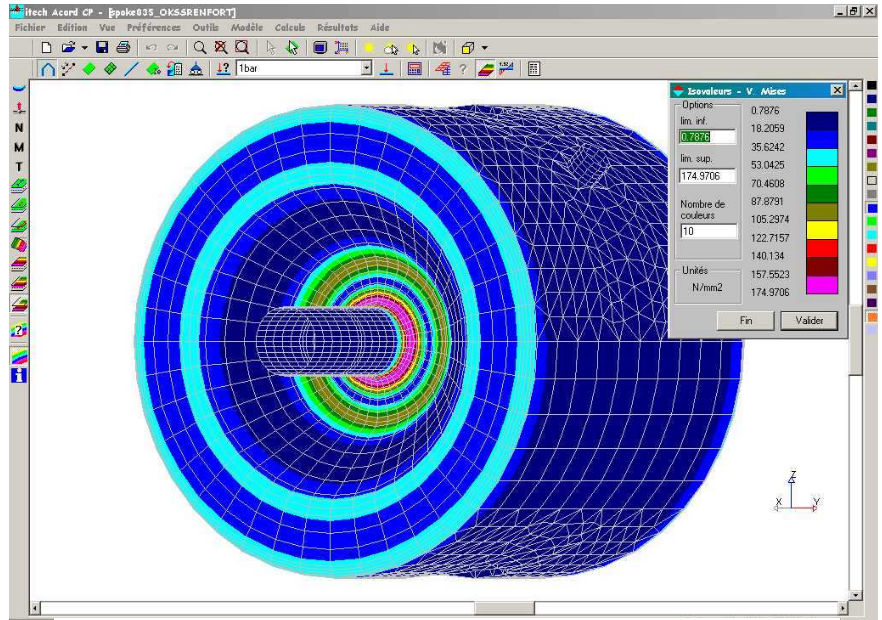
Thickness (mm)	Peak V.M stress (MPa)
2	372
3	175
4	102
5	67

Yield strength exceeded

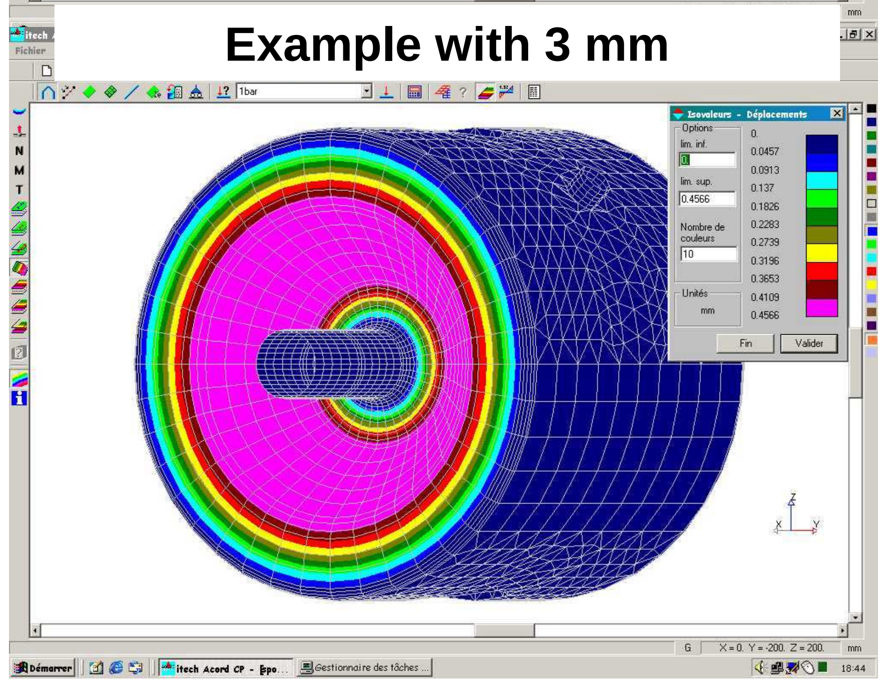
Cost : 3600€/mm & 8 kg

⇓

!!! Stiffeners !!!



Example with 3 mm



Under vacuum load @ 1 bar

Thickness: 3 mm

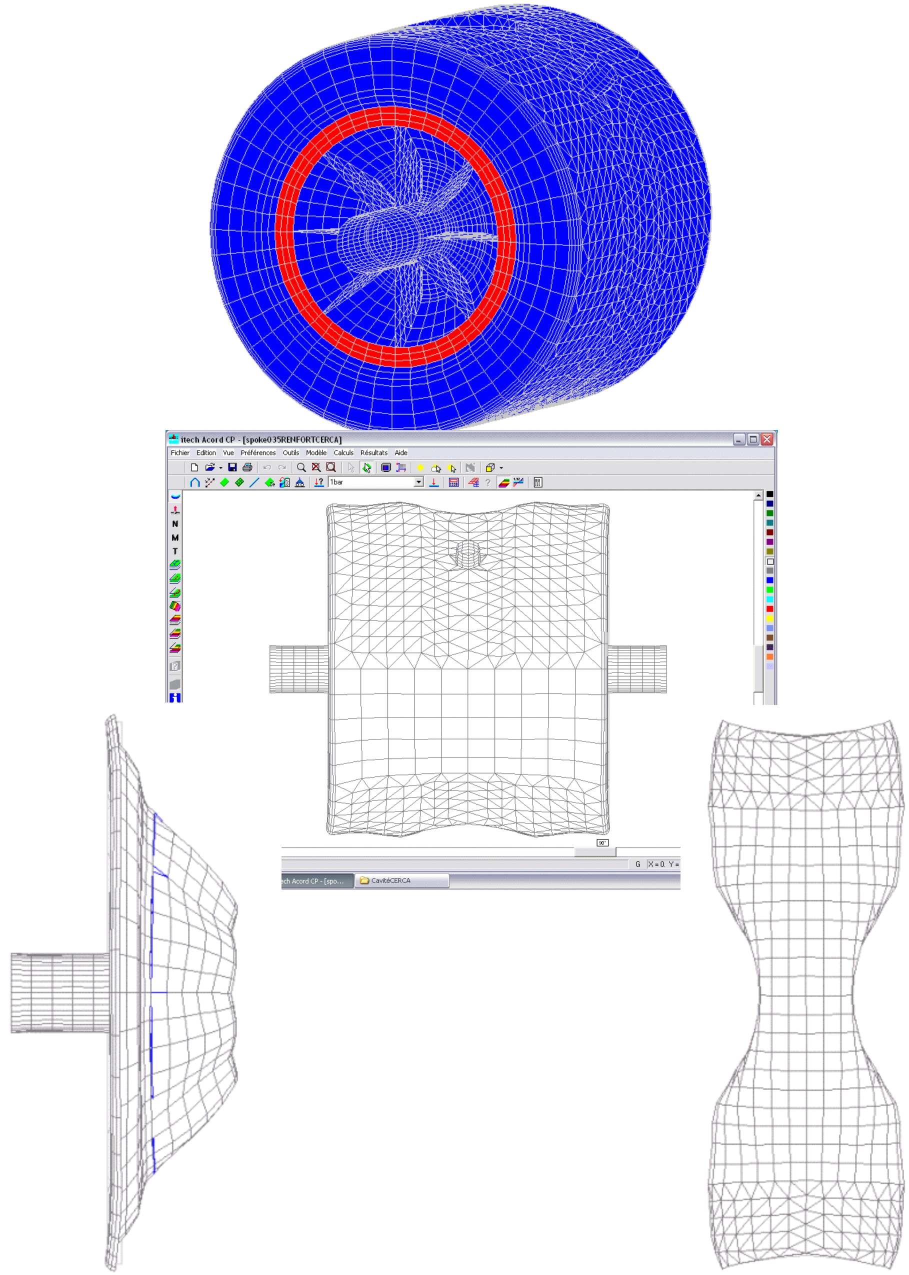
Cavity with 8 stiffeners

& a ring (2 mm thick)

Peak V.M stress (MPa)	Peak displacement (mm)
37.3	0.057

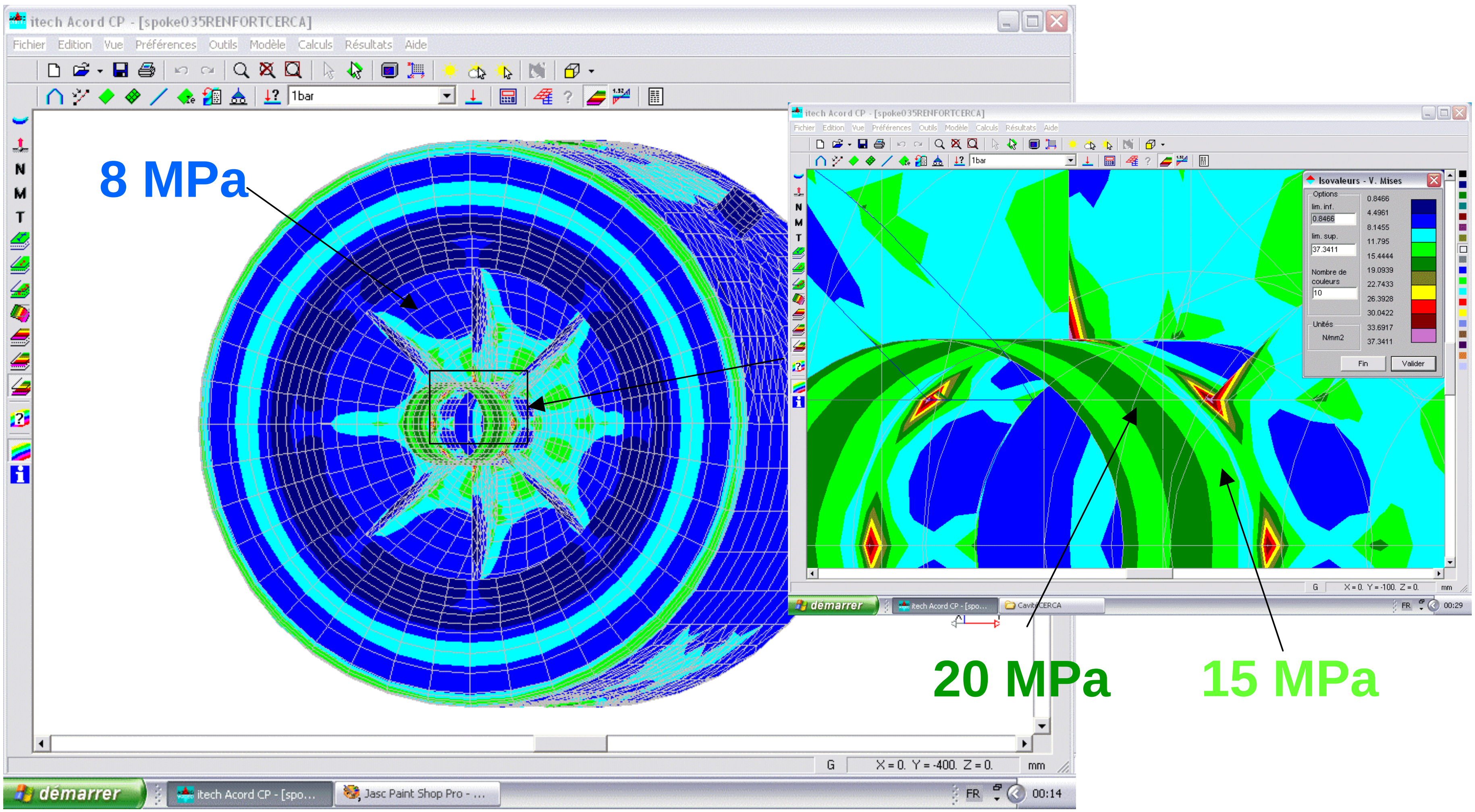
NB: Both beam tube ends fixed

No change with thicker stiffeners (3 mm to 5 mm)



Under vacuum load @ 1 bar

Location of stress



Under vacuum load @ 1 bar

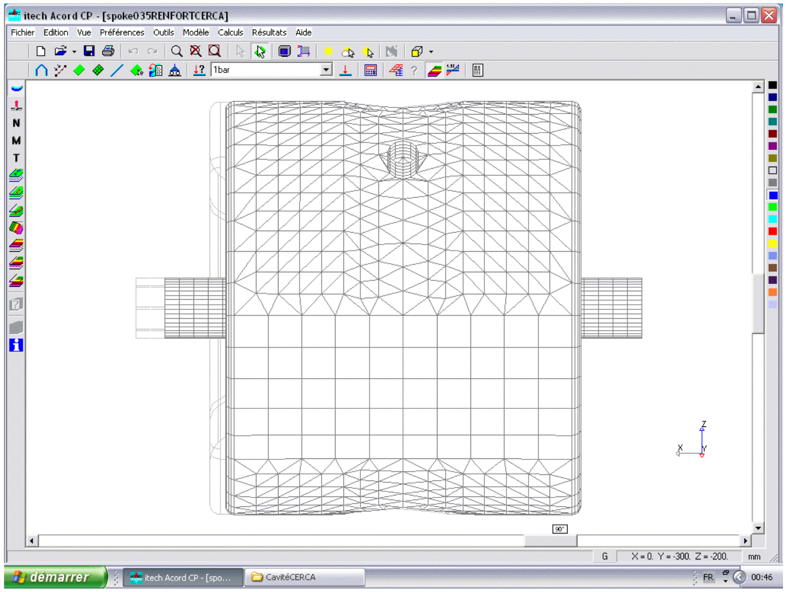
Calculations with one end free

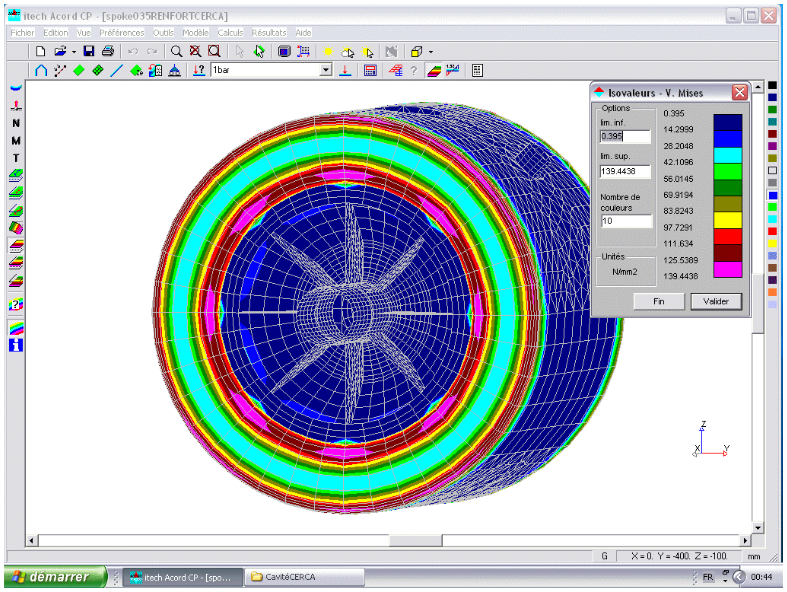
Peak V.M stress (MPa)	Peak displacement (mm)
139	2.38

⇓

We need to fix the cavity under vacuum load

So we used the test bench designed for the 5-cell cavity





Tuning

Cavity stiffness value

- 50 MPa reached for 0.86 mm
- 3500 N/mm

measurements

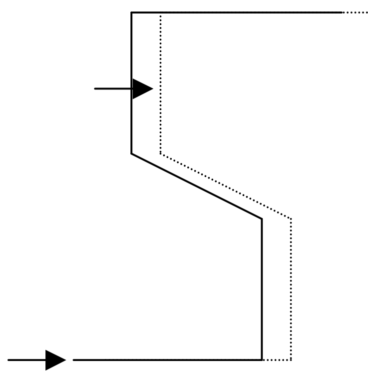
~2500 N/mm (error: 40%)

Sensitivity

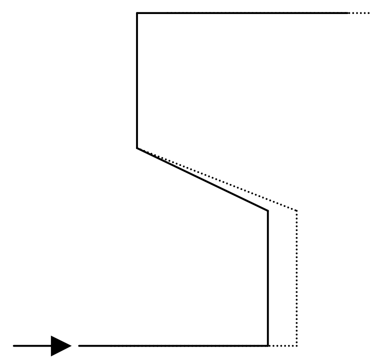
- between 450 and 800 kHz/mm (estimation with MAFIA)

measurements

~550 kHz/mm



450 kHz/mm



800 kHz/mm

Vibration modes

Frequencies in Hz of the first modes

Mode 1	97
Mode 2	149
Mode 3	287
Mode 4	303
Mode 5	336

→ **Torsion/beam axis**

→ **Oscillation along the beam axis**

Deformations

NB: Both beam tube ends fixed

→ NO DANGER ?

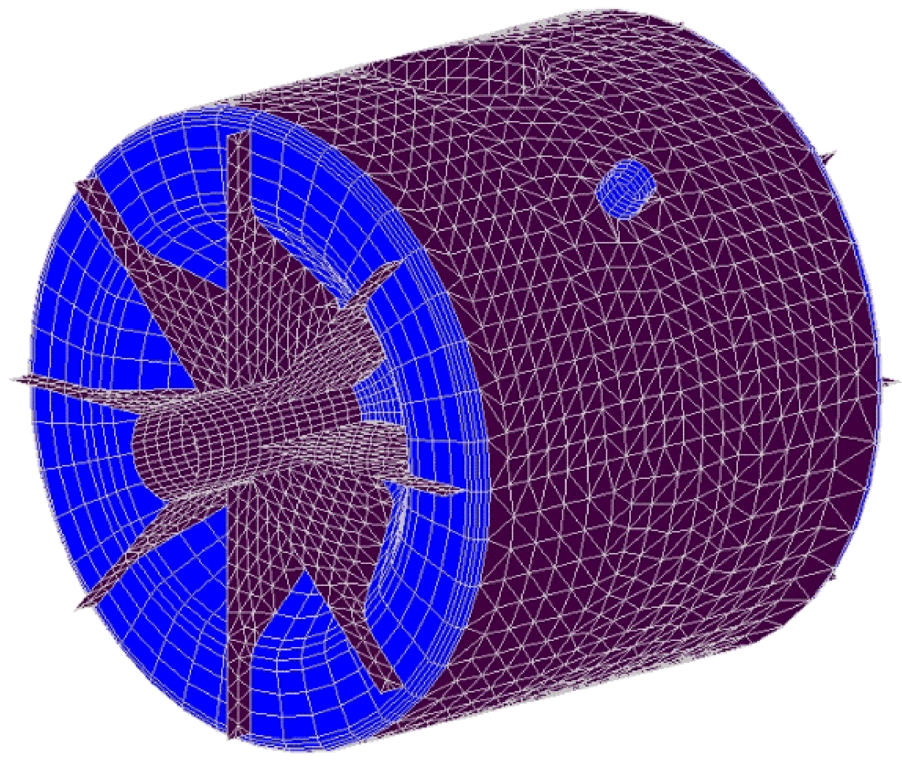
Conclusion

• Cavity is OK for cryogenic test (P~1 bar in cryostat)

• Cavity is probably not OK in an “accelerator” configuration (P up to 2 bars during cool down)
$\rightarrow$ New stiffeners (in study)

Discussion

• Advantages & Drawbacks in comparison with the stiffening ring option ?



Discussion on "XADS/Eurisol Mechanical Design" by Guillaume Olry

The tuning forces and sensitivities for the Orsay design were reiterated. The tuner needs to provide 2500 N/mm, which is 40% lower than the simulated value. Olry pointed out that all mechanical simulation results were worse than the measured data. The origin of this systematic deviation are not understood yet.

The tuning sensitivities were reasonably well in agreement with the simulations. MAFIA predicted 800 kHz/mm, while 600 kHz/mm were measured. The MAFIA discretization was selected static to exclude frequency changes due to a changed discretization.

Mechanical Design of the AAA β = 0.175 Spoke Resonator

Dale Schrage, LANL

The β = 0.175, 2-gap, 350 MHz spoke resonator cavity for the LANL Advanced Accelerator Applications (AAA) Program is an integrated engineering and physics design of cavity to follow the 6.7 MeV RFQ on the LEDA Beamline. Modern RF cavity and structural analysis codes have allowed this cavity to be built without prototyping. The cavity design process is described.

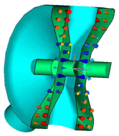
LA-UR-02-6141

MECHANICAL DESIGN OF THE AAA β =0.175 SPOKE RESONATOR

Dale Schrage
LANL

Workshop on the Advanced Design of Spoke Resonators

Los Alamos, NM, USA
October 7 and 8, 2002



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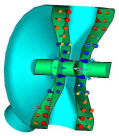
ENGINEERING & DESIGN

- **Cavity FEA: Richard LaFave**
- **Cavity Mechanical Design: Phil Roybal**
- **Cavity Physics Design: Frank Krawczyk**
- **Advisors: Ken Shepard, Jean DeLayen, Brian Rusnak**

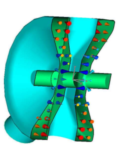


CAVITY REQUIREMENTS

PARAMETER	VALUE
Resonant Frequency	350 MHz
Beam Current	13 - 100 mAmps
# of Gaps	2
Geometric β	0.175
Operating Temperature	4.5 K

CAVITY DESIGN PROCEDURE

1. CREATE UNIGRAPHICS MODEL
2. EXPORT TO MAFIA
3. RUN MAFIA
4. ITERATE STEPS 1, 2, & 3 UNTIL SATISFIED
5. EXPORT MODEL TO SOLIDWORKS
6. CREATE STRUCTURAL GEOMETRY
7. CREATE MESH
8. EXPORT TO COSMOS/M
9. RUN CAVITY MODULE (MICAV)
10. APPLY STRUCTURAL LOADS
11. RUN STRUCTURAL MODULE
12. TRANSFER RESULTS TO CAVITY MODULE
13. RUN CAVITY MODULE FOR FREQUENCY SHIFT



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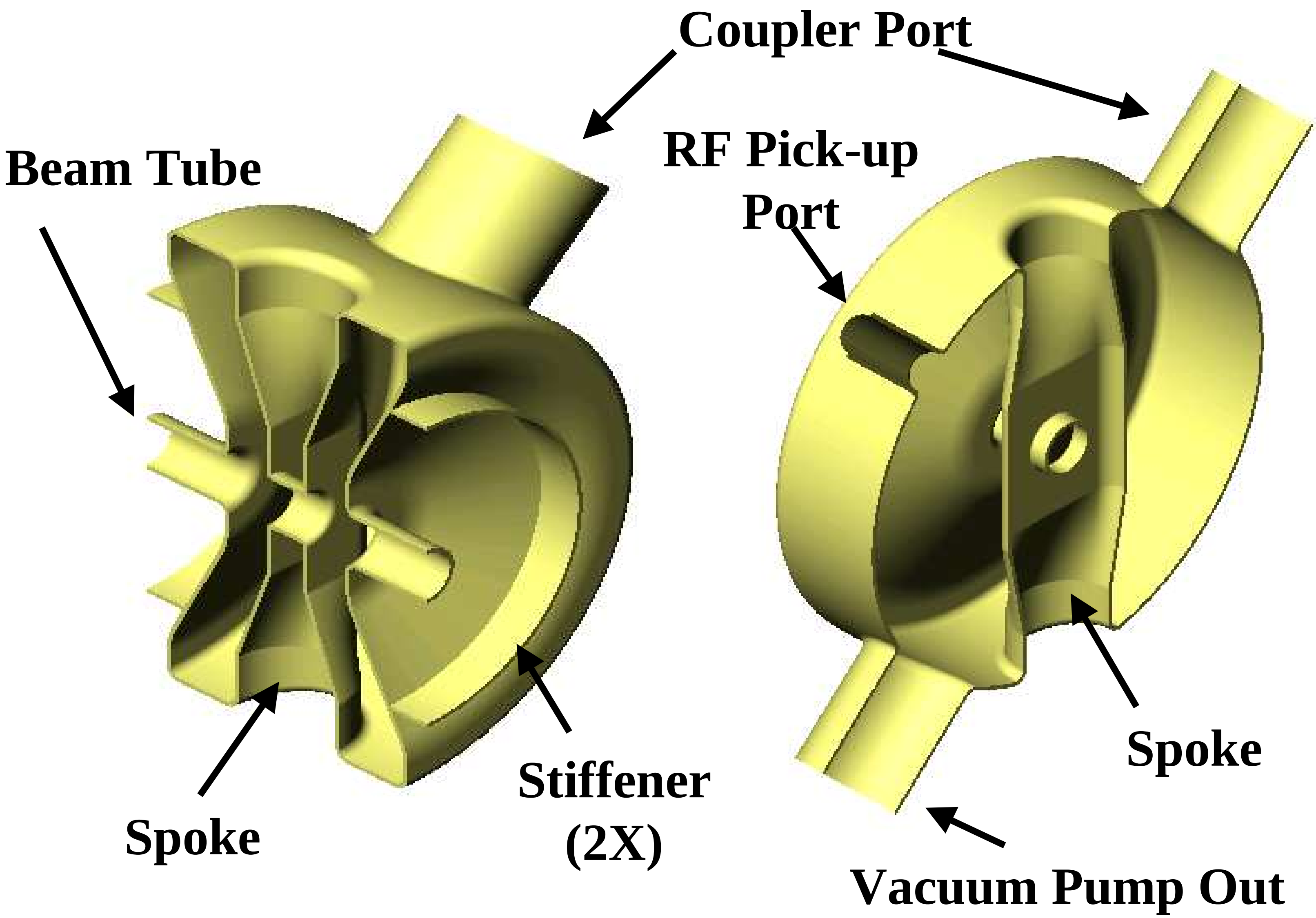
AAA β = 0.175 SPOKE CAVITY

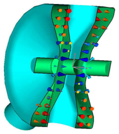


SPECIAL FEATURES

- **ANNULAR STIFFENERS: USE TUNER FRAME FOR RIGIDITY**
- **CONFLAT™ FLANGES: MUST BE BRAZED ON**
  - **NEXT TIME CONSIDER NIOBIUM/TITANIUM IF TIME AVAILABLE FOR TESTING CONCEPT**
- **TITANIUM COLLARS: FOR TITANIUM HELIUM VESSEL, CAN BE WELDED DIRECTLY TO NIOBIUM**
  - **ALTERNATIVE IS STAINLESS STEEL HELIUM VESSEL**

STIFFENER CONSIDERATIONS

- **ANNULAR STIFFENERS:**
  - **CAVITY NOT STANDALONE RIGID**
  - **FACILITATES TUNING**
- **RADIAL STIFFENERS:**
  - **CAVITY IS STANDALONE RIGID**
  - **TUNING FORCES ARE HIGHER**

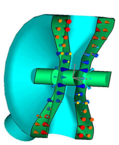


STRUCTURAL ANALYSIS & TEST RESULTS

THERE WAS GOOD AGREEMENT WITH PREDICTIONS

		PREDICTED	MEASURED
MANUFACTURING TUNING SENSITIVITY	kHz/mm	770	747
STRUCTURAL TUNING SENSITIVITY	kHz/mm	894	783
STIFFNESS	N/mm	$1.02\ 10^4$	$0.52\ 10^4$
BCP MATERIAL REMOVAL	kHz/μ	3.6	
VACUUM LOAD	kHz/atm	-44	
THERMAL FREQUENCY SHIFT to 4K	kHz	515	

EFFECTS OF BCP, VACUUM, & TEMPERATURE WILL BE MEASURED SOON



Discussion on "Mechanical Design of the AAA β=0.175 Spoke Resonator" by Dale Schrage

There was no discussion on this talk.

Tuner Designs

Brian Rusnak: "*Tuner Design for RIA*"
(Abstract | Viewgraphs | Discussion)

Dale Schrage: "*Tuner for the AAA Beta=0.175 Spoke Resonator*"
(Abstract | Viewgraphs | Discussion)

Tuner Design for RIA

B. Rusnak, Lawrence Livermore Laboratory

Compensating microphonic-induced detuning on the superconducting structures of the RIA Driver Linac will play a more important role due to the light beam loading in the machine. Unlike recent SRF applications where the beam-loaded bandwidth is roughly comparable to or greater than the microphonic detuning window, RIA's beam-loading is a factor of 10-100 smaller. The impact of this light beam loading and some ways to compensate microphonic detuning shall be discussed.

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Fast Tuner Development for RIA

Spoke Cavity Workshop - Los Alamos National Lab

October 7-8, 2002

Brian Rusnak

Microphonic Effects on the RIA Driver (and RIB) Linacs Strongly Influence the RF Design and Cost

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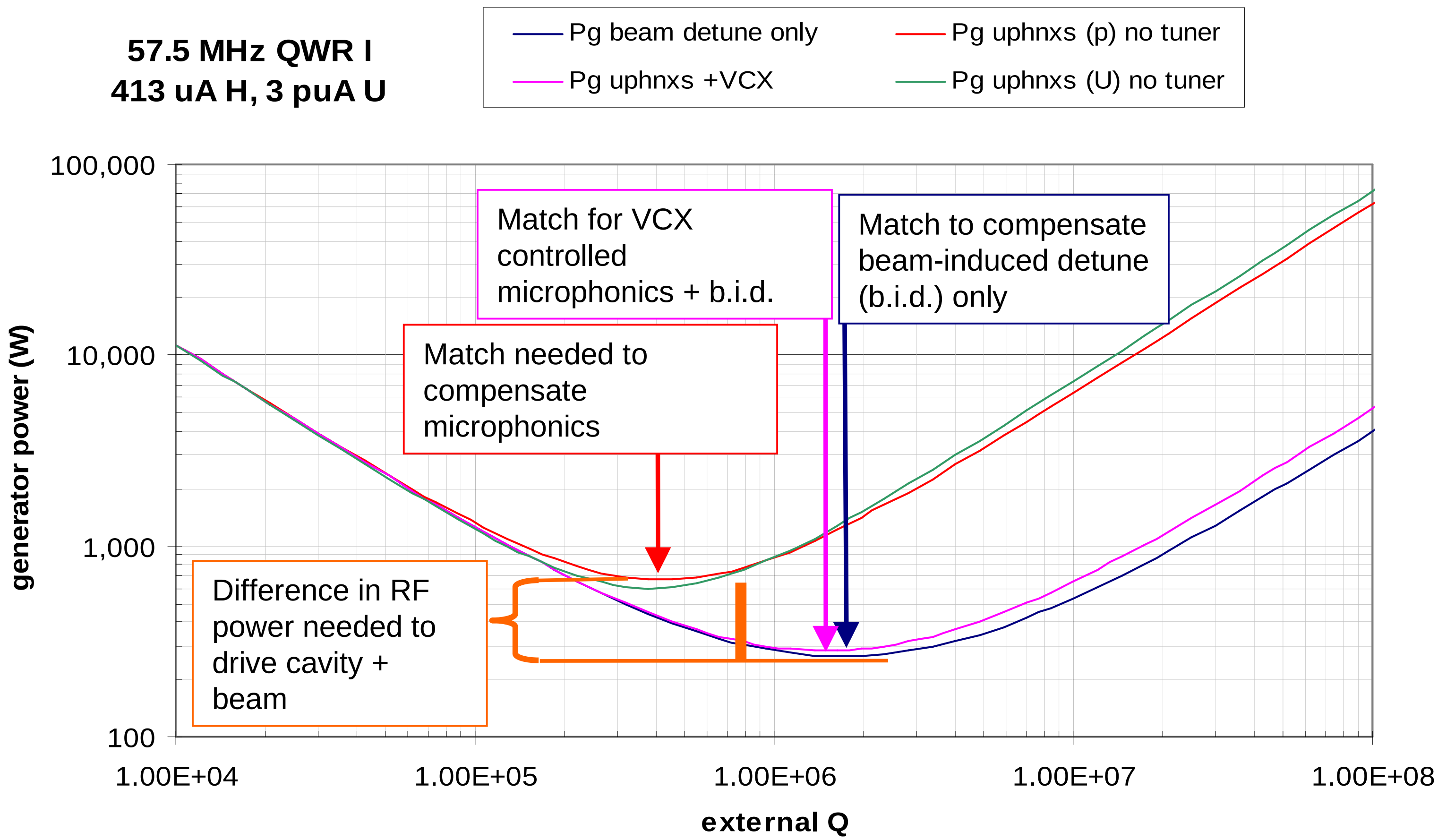
- RIA is not like other linacs where beam loading is comparable to the microphonic detuning
- The microphonic control window for RIA is expected to be on the order of 50-150 Hz, which is greater than the beam loaded bandwidth
  - Microphonics at ~ 7-15 Hz with a multiplier to achieve margin of ~ 10-12

linear accelerator	operating frequency (MHz)	loaded Q	bandwidth (Hz)
CEBAF/Jefferson Lab	1497	2.2×10^6	680
SNS/ORNL	805	7.0×10^5	1,150
APT design/LANL	700	2.2×10^5	3,182
RIA – 115 MHz – U beam	115	8.7×10^6	13
RIA – 345 MHz – U beam	345	1.3×10^7	27
RIA – 805 MHz – U beam	805	8.3×10^8	1

- Light beam loading on the Driver and RIB linacs necessitates that microphonic detuning of the SRF cavities be addressed
  - Heavy ion machines have limited and widely varying beam currents across species driven primarily by ion source considerations
  - Stable operation on species and rapidly retuning the machine are important for customer satisfaction

“Idealized” Generator Power Related to a Q_x Setpoint for a Fixed Beam Current

57.5 MHz QWR I
413 uA H, 3 puA U



$$P_{gen} = \frac{P_c}{4}\left\{\frac{2I_o R_a}{V_c}\left[\left(1+\frac{Q_x}{Q_0}\right)\cos(\phi) - 2Q_x\delta\sin(\phi)\right] + \left[\frac{(Q_0+Q_x)^2 + 4(Q_0 Q_x \delta)^2}{Q_0 Q_x}\right] + \left(\frac{I_o R_a}{V_c}\right)^2 \frac{Q_x}{Q_0}\right\}$$

Low-β Driver Cavities Power Required Curves from 57.5 - 345 MHz

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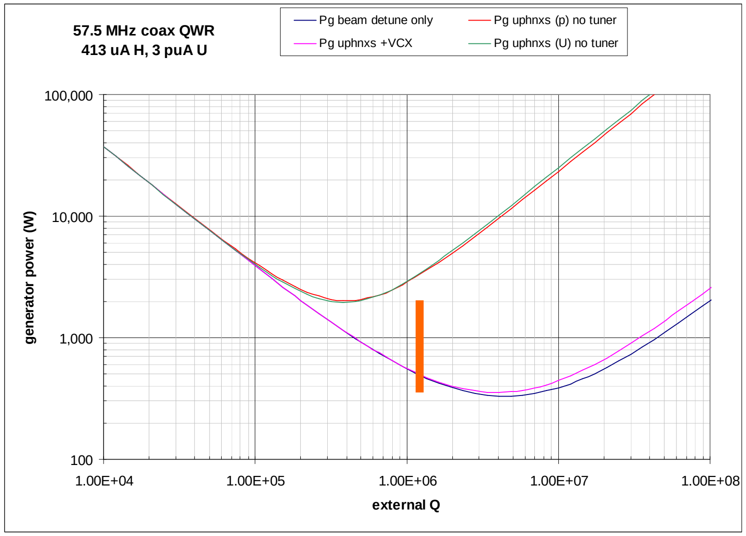

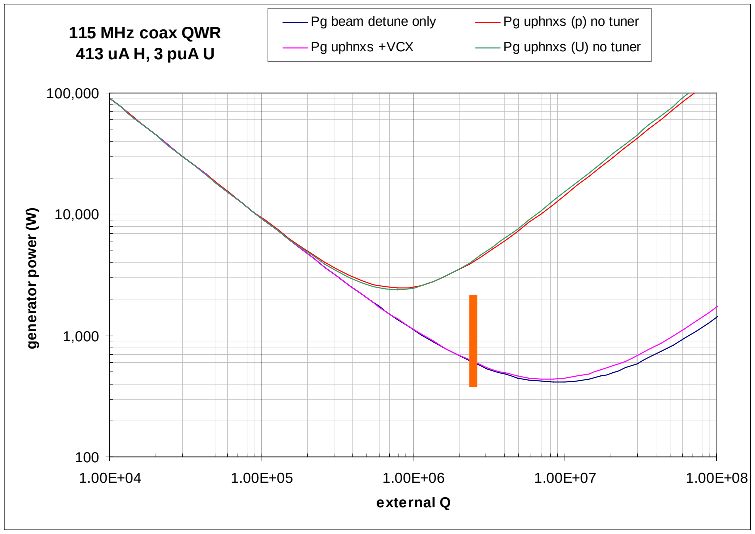

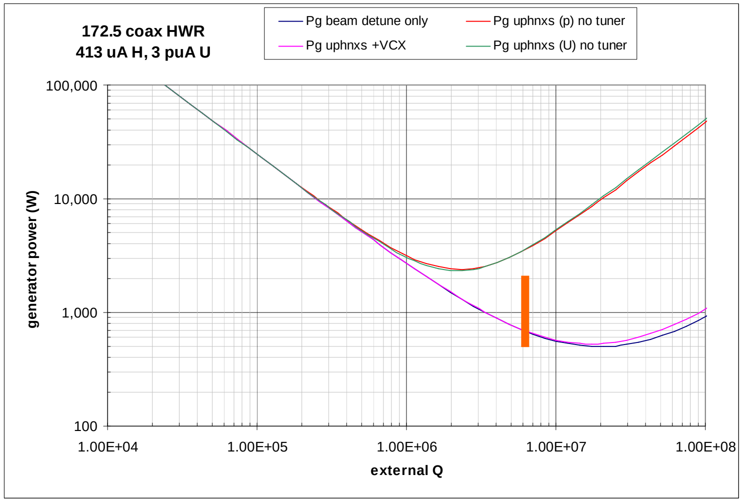

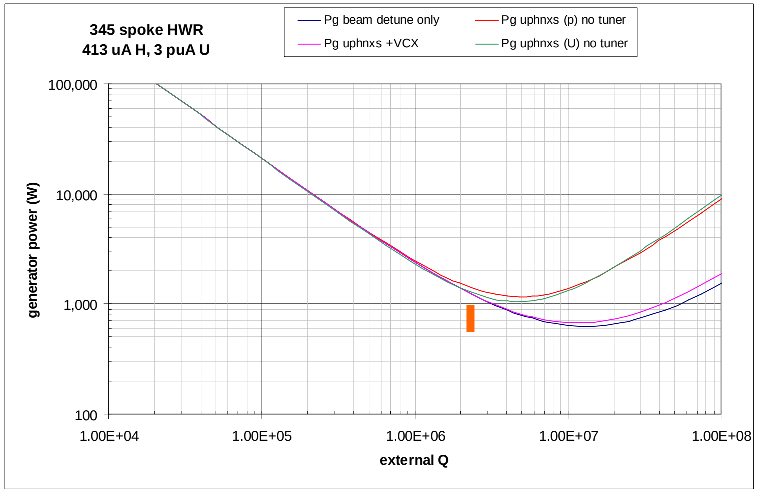

805 MHz Elliptical Cavity Power Requirement Curves

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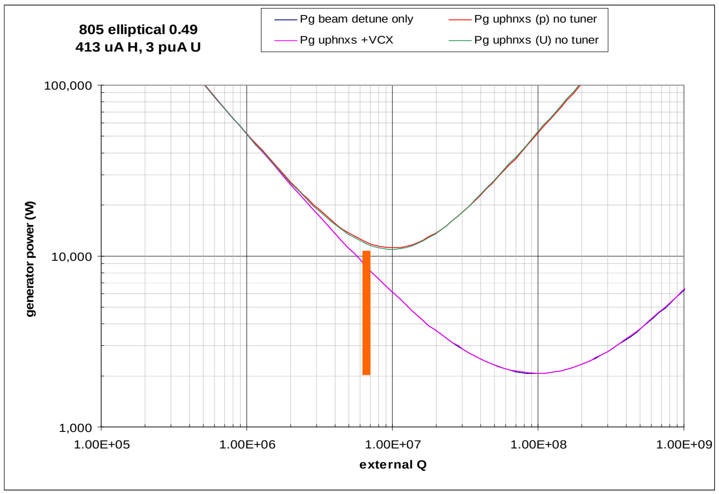

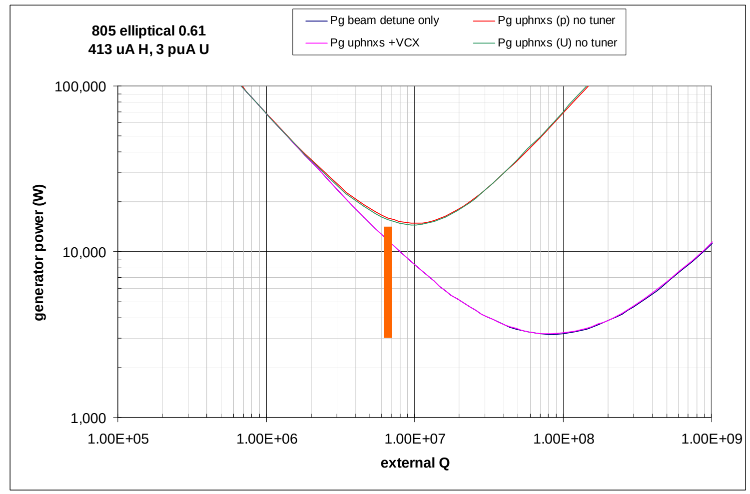

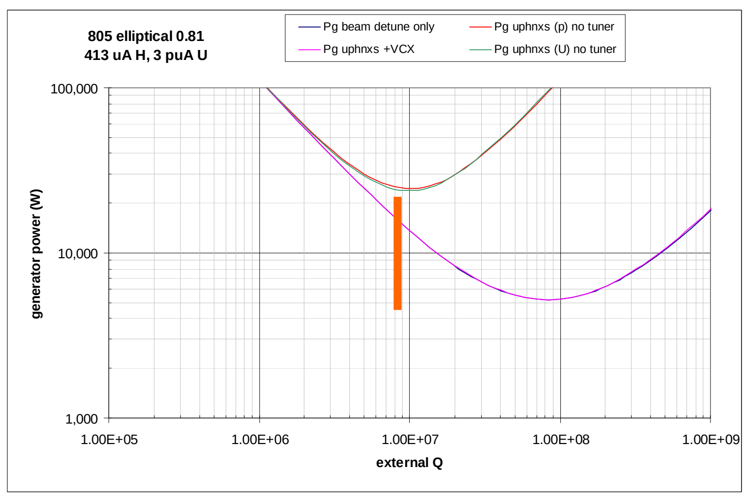

Comparative Summary of Overcoupled and VCX Cases Demonstrating Impact

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	------- Overcoupled Case ------		- VCX Tuner Compensated -	
cavity type	**installed**	**section**	**installed**	**section**
	RF power	**cost**	**RF power**	**cost**
low β	**(W)**	**(k$)**	**(W)**	**(k$)**
57.5	160,000	2,155	30,000	1,160
115	225,000	2,424	45,000	1,576
172.5	520,000	7,522	104,000	3,642
345	160,000	5,508	160,000	5,098
low β subtotal	**1,065,000**	**17,609**	**339,000**	**11,476**
high β				
805 - 0.49	960,000	7,749	240,000	5,039
805 - 0.61	1,920,000	12,412	320,000	8,140
805 - 0.81	1,400,000	7,066	280,000	3,561
high β subtotal	**4,280,000**	**27,227**	**840,000**	**16,740**
LN lines low β				**175**
LN lines hi β				**225**
linac totals	**5,345,000**	**44,836**	**1,179,000**	**28,616**

Low β cost savings: 6.1 M$

High β cost savings: 10.5 M$

- Reduced cost primarily due to the factor of 3-5 less installed RF power, smaller RF couplers, transmission lines, and components which more than offsets the cost of the tuner and pulser.

- Costs include estimates for running cryogenic LN lines in the tunnel.

Approaches to Compensate Microphonic Detuning

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- Microphonic detuning is more a cost and implementation challenge than a technical show stopper
- It comes down to where the effort and resources are placed:
  - Overcoupling: costly, wastes RF, but is effective
  - VCX fast tuning: efficient, needs further development
  - Cavity stiffening: mechanical engineering design challenge, especially to accommodate slow and bench tuning
- Based on the operational agility and the effectiveness of the VCX fast tuner demonstrated at the ATLAS heavy ion linac, development in this area is being pursued in the baseline design for RIA
  - Phase I: extend ATLAS design to 345 MHz using distributed element model
  - Phase II: explore applicability to elliptical cavities with much higher stored energy and frequency

Design Drawing of Distributed-Element VCX Tuner at 345 MHz

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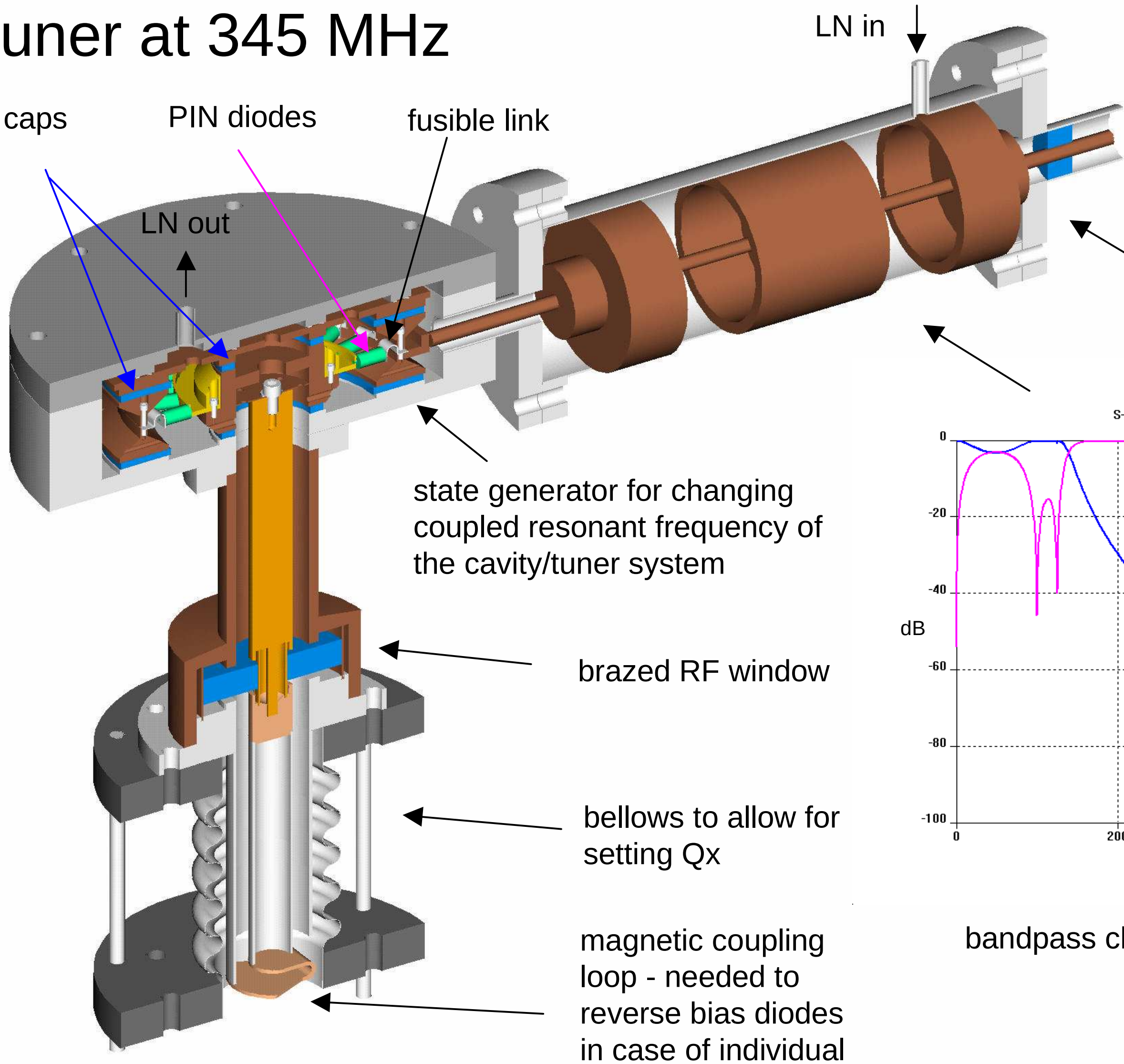

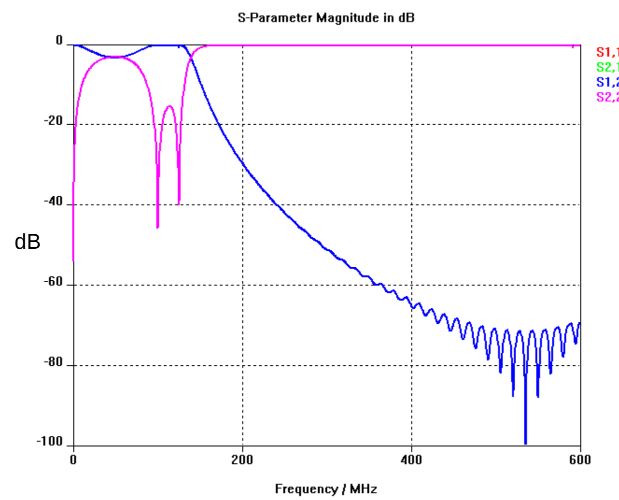

bandpass characteristics of LP filter

Development Work Needed

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- RF modeling (Microwave Studio)
  - voltages on state generator components
  - evaluating impedance at different frequencies
  - determine power densities
  - finish modeling window
- Device prototyping
  - machine parts
  - measure at low power
  - fine tune as necessary
  - test on cavity
- Pulser work
  - evaluate present pulser design
- Additional evaluation work needs to be done looking at applicability to elliptical cavities, as this is where the largest cost savings (and largest development effort) would be

Discussion on "Tuner Design for RIA" by Brian Rusnak

The question was asked, how the VCX compares to a PZT fast tuner. Shepard answered that so far PZT is only proposed for feed forward compensation of pulsed operation, while VCX is proposed to control microphonics. Pagani added that there are investigations for TESLA to extend the use of PZTs to microphonics compensation too.

The experience base of PZTs was discussed next. There was preliminary work at LANL on the Scruncher cavity, which was a single cell with a small mode spectrum. There was general agreement that PZT needs some long term demonstration.

Shepard next pointed out that the availability requirements for RIA require a good understanding of the microphonics issue (e.g. due to coupling of the resonator mechanical resonances to the excitations from the cryo system). The resonances are in part due to a complex 2-phase flow in the cryogenic system, this effect is already seen in the ATLAS accelerator. Mike Kelly added that pressure changes as small as 1-2 Torr can be seen in the system.

Solutions to mitigate microphonics issues are either overcoupling at the price of a huge increase in the power needed (requires 10 and 50 kW couplers), or a very good and fast RF control (requires only 1 and 5 kW couplers). He and Rusnak believe that the VCX could be a good engineering solution for stable operation at reasonable cost, whose feasibility has to be demonstrated however.

To further emphasize the importance of microphonics he commented that thin solid niobium resonators as proposed for RIA are much more sensitive to microphonics than niobium sputtered on copper cavities as used by Legnaro and CERN.

Kelley proposed to attach the origin of the problem in the cryosystem, instead of putting the burden onto a complicated RF-control in the resonators. Shepard agreed that it is desirable to study this option.

The cost advantages shown for the VCX include all secondary components required for their operation. Facco pointed out that VCX tuners add complexity to the system due to operating "multiple--component" devices in a cryogenic environment. Rusnak agreed that an overall system study needs to be done to assess the added risk vs. the cost reduction.

The final remark of the discussion pointed out that this is probably a 4K operation problem, as TESLA in its 2K system does not see large microphonics effects.

Tuner for the AAA $\beta = 0.175$ Spoke Resonator

Dale Schrage, LANL

A pre-conceptual design of a tuner for the $\beta = 0.175$, 2-gap, 350 MHz spoke resonator cavity for the LANL Advanced Accelerator Applications (AAA) Program will be presented. In addition to static adjustments of the cavity RF frequency, the requirements of operation of a waste transmutation facility necessitate that the cavity be rapidly (< 300 msec) detuned to compensate for the effects of a failed cavity or power coupler.

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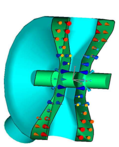
TUNER FOR THE AAA β=0.175 SPOKE RESONATOR

Dale Schrage
LANL

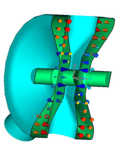
Workshop on the Advanced Design of Spoke Resonators

Los Alamos, NM, USA
October 7 and 8, 2002



AAA TUNER

- **PRELIMINARY CONCEPT BY BOB GENTZLINGER & PHIL ROYBAL**
- **TUNER REQUIREMENTS PRESENTLY NOT FIRMLY SPECIFIED**
  - **MAIN REQUIREMENT IS TO DE-TUNE CAVITY BY 30 kHz IN < 150 msec**
- **MUST INTEGRATE INTO CAVITY, HELIUM VESSEL, AND CRYOMODULE DESIGN**



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PRELIMINARY TUNER REQUIREMENTS

β = 0.175, 2-GAP CAVITY, FREQUENCY SENSITIVITY ~ 1.0 MHz/mm
1485 kg/mm

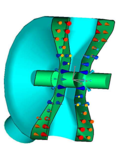
β = 0.340, 5-GAP CAVITY, FREQUENCY SENSITIVITY ~ 0.2 MHz/mm
1485 kg/mm

FAST TUNING REQUIREMENT:

FOR ADTF: MUST TAKE CAVITY OFF RESONANCE IN 300 msec
ALLOW 150 msec TO CHANGE CAVITY FREQUENCY 30 kHz
β = 0.34, 5-GAP CAVITY IS WORST CASE
δ = 0.15 mm, 223 kg

SLOW CAVITY TUNING REQUIREMENT:

FOR ADTF: β = 0.34, 5-GAP CAVITY IS WORST CASE
δ = 2.5 mm, 3712 kg



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PRELIMINARY TUNER CONCEPT

- **SEPARATE SYSTEMS FOR FAST AND SLOW REQUIREMENTS**
- **USE SCREW-DRIVE MECHANISM FOR SLOW CAVITY TUNING REQUIREMENT**
- **USE PIEZOELECTRIC ACTUATOR FOR FAST TUNING REQUIREMENT**
- **BOTH ACT ON CAVITY BEAM TUBE**

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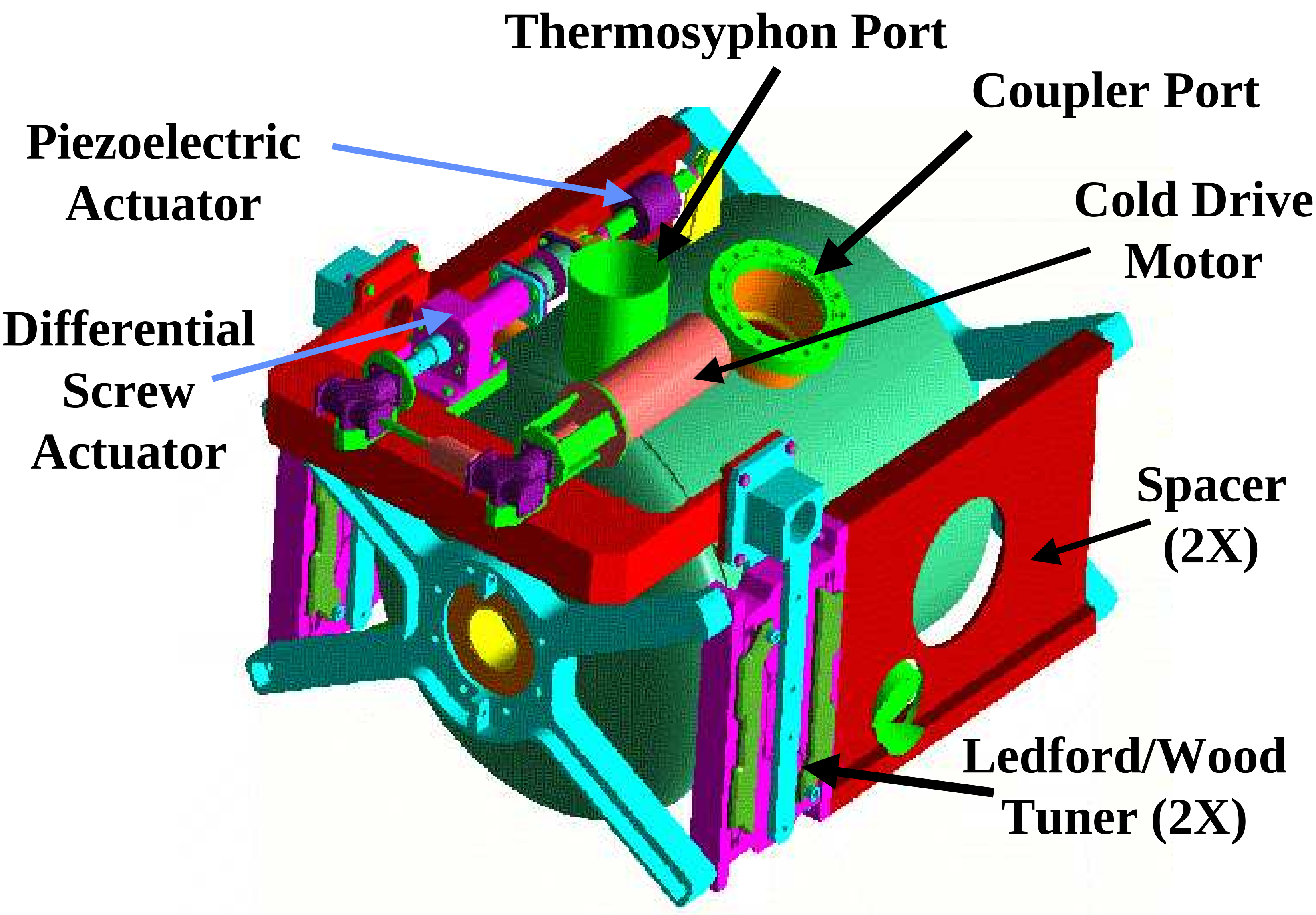
CAVITY ASSY w/TUNER



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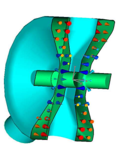
UNDESIRABLE FEATURES

- **MOTOR INSIDE CRYOMODULE**
  - CAREFUL SELECTION REQUIRED
- **GEARBOX INSIDE CRYOMODULE**
  - LUBRICATION IS A CONCERN
- **PZT INSIDE CRYOMODULE**
  - SOME PROTOTYPING WILL BE REQUIRED



Discussion on "Tuner for the AAA β=0.175 Spoke Resonator" by Dale Schrage

Schrage’s presentation covered mechanical and PZT tuners. It was asked, how magneto-restrictive tuners fit into the needs of these applications. Schrage answered, that the applicability of those might for the time being be limited to low force, low displacement applications, which is not suitable. Pagani confirmed that TESLA looked at those and disregarded them, as they saw too many additional problems that would need to be solved (e.g. magnetic shielding).

Fabrication

Ken Shepard/Joel Fuerst: "*2-cell Spoke Cavity Fabrication*"
(Abstract | Viewgraphs | Discussion)
Jean Lesrel: "*The Fabrication of the First French Spoke Prototype*"
(Abstract | Viewgraphs | Discussion)
Dale Schrage: "*Fabrication of the AAA Beta=0.175 Spoke Resonator*"
(Abstract | Viewgraphs | Discussion)

RIA Project: Spoke-cavity Design

K. Shepard, Argonne National Laboratory

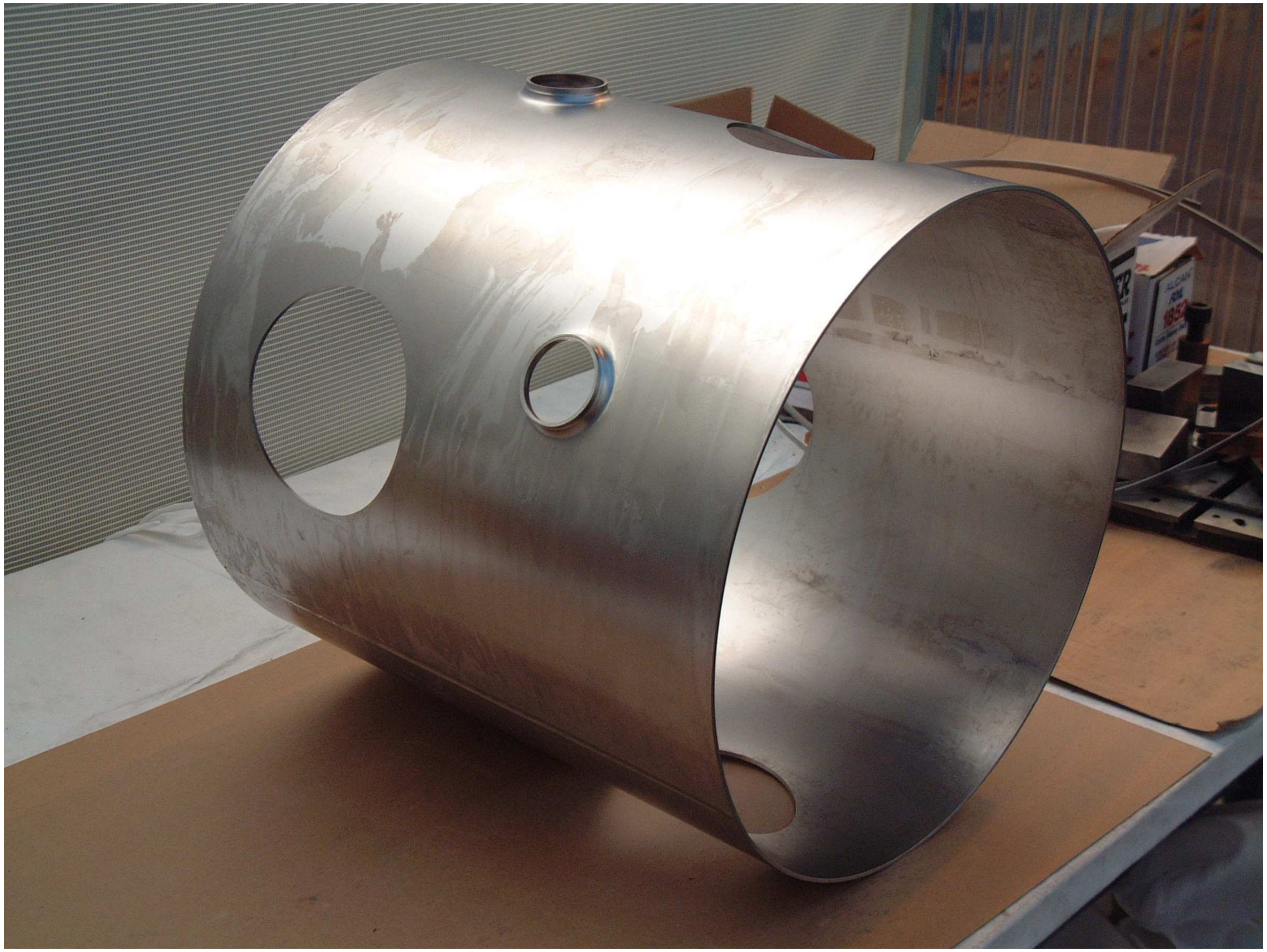
Geometry and electromagnetic properties of 345 MHz multiple-spoke cavity designs for RIA are discussed. Mechanical details and current status of prototype multiple-spoke cavities are presented.

2-cell Spoke Cavity Fabrication

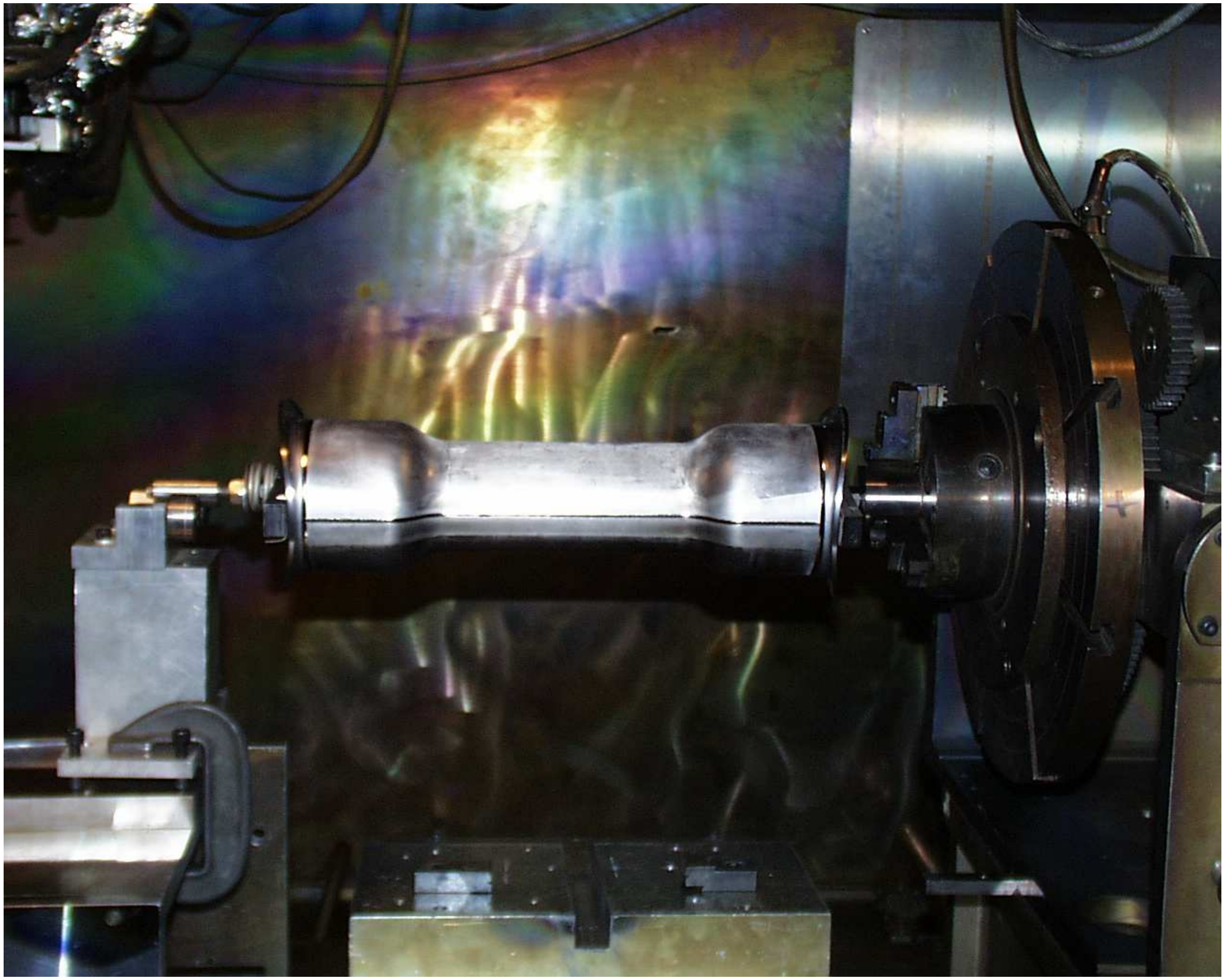
Joel Fuerst
Argonne National Laboratory

Rolling the Nb shell

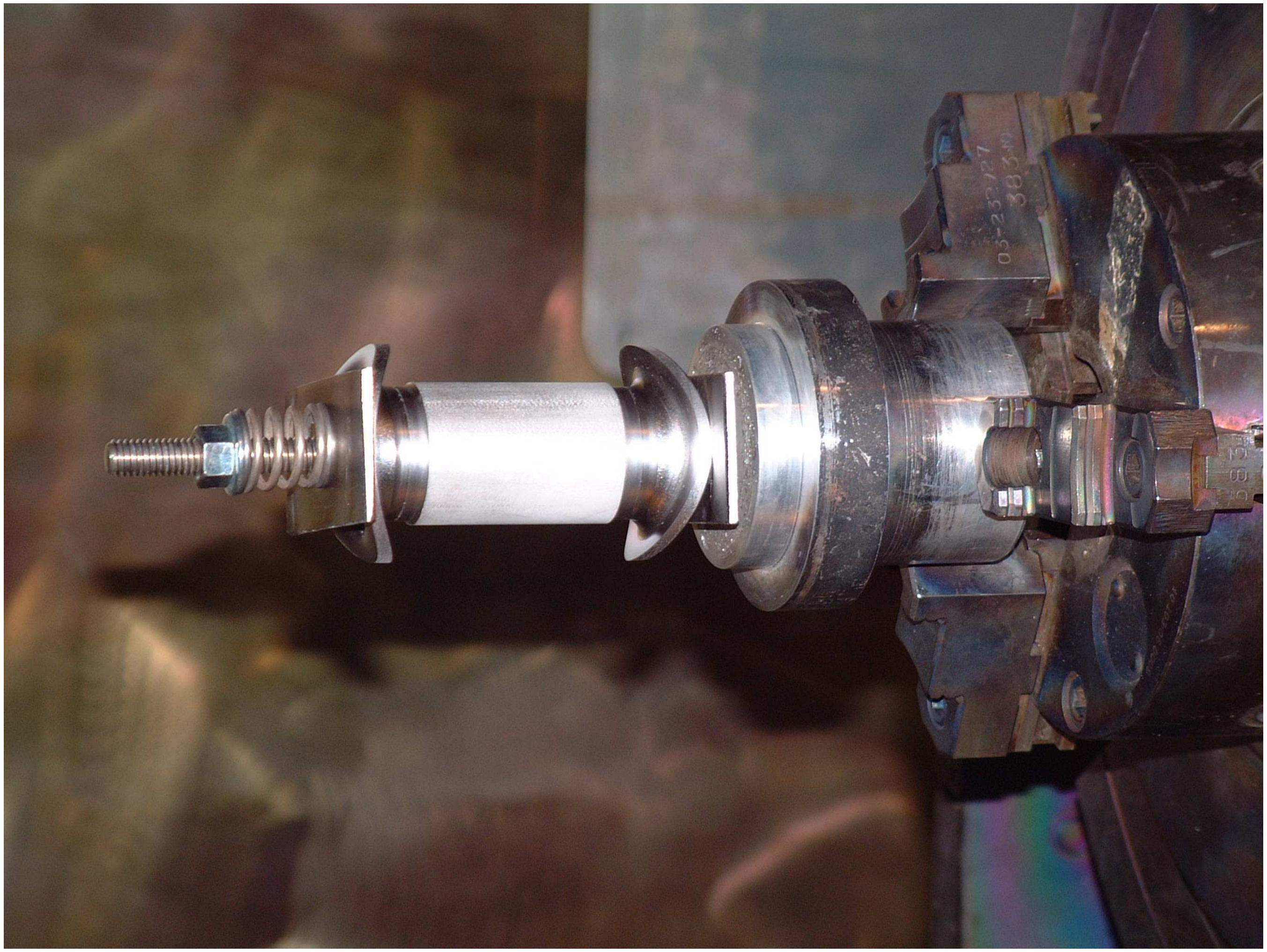
Completed Nb shell with pulled ports and spoke bores



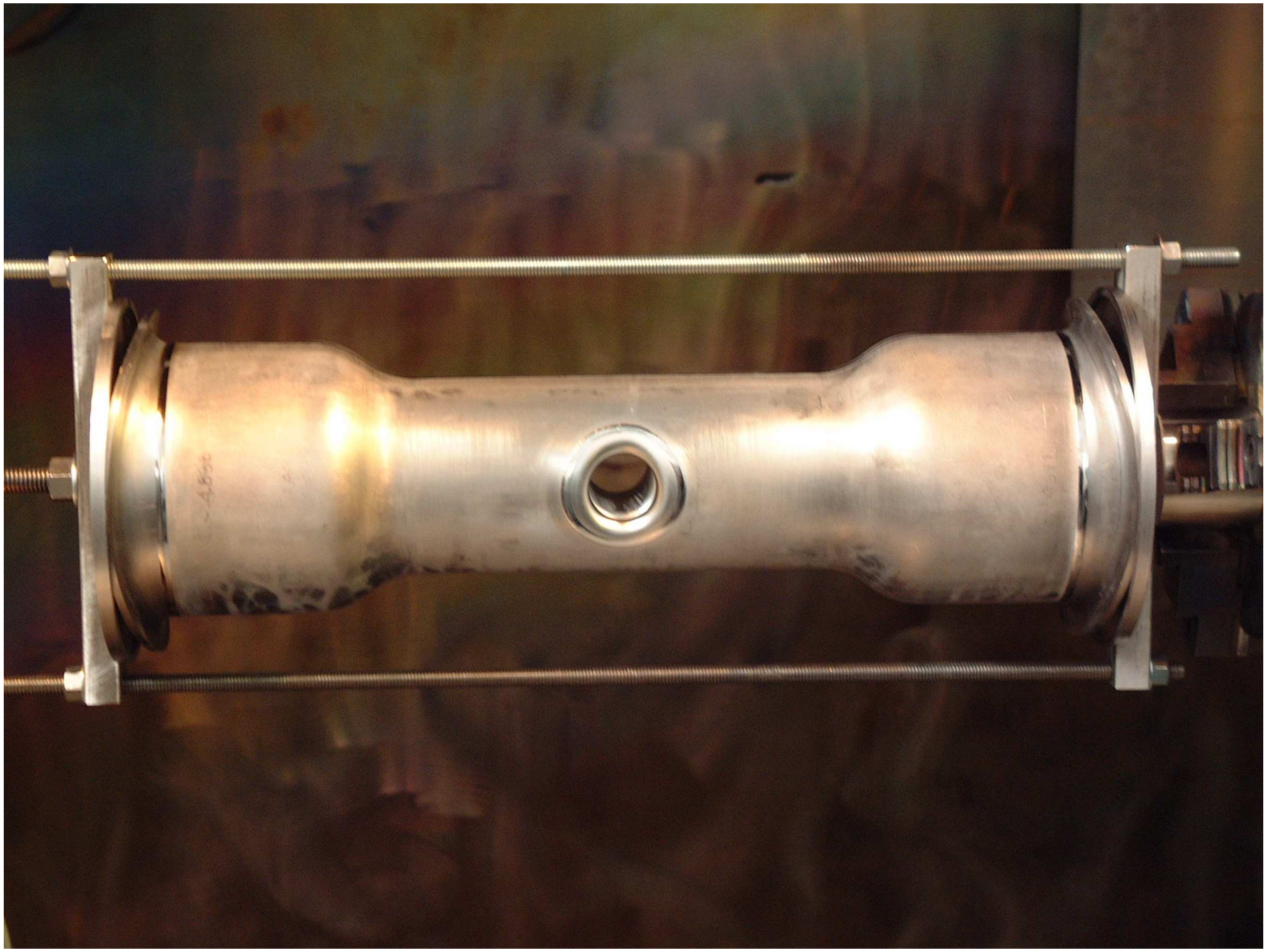
Setup for spoke end transition saddle weld



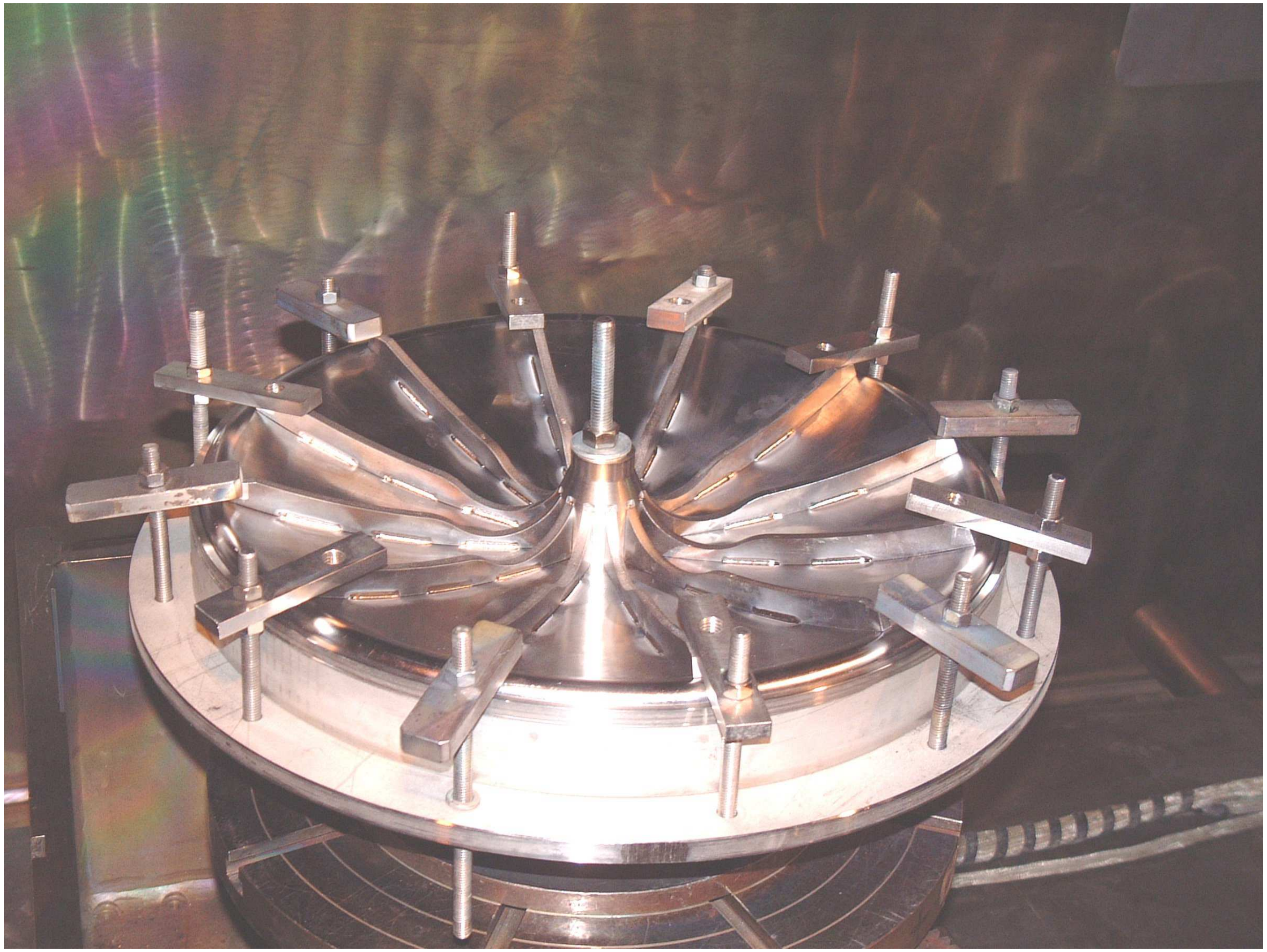
Beam tube transition saddles



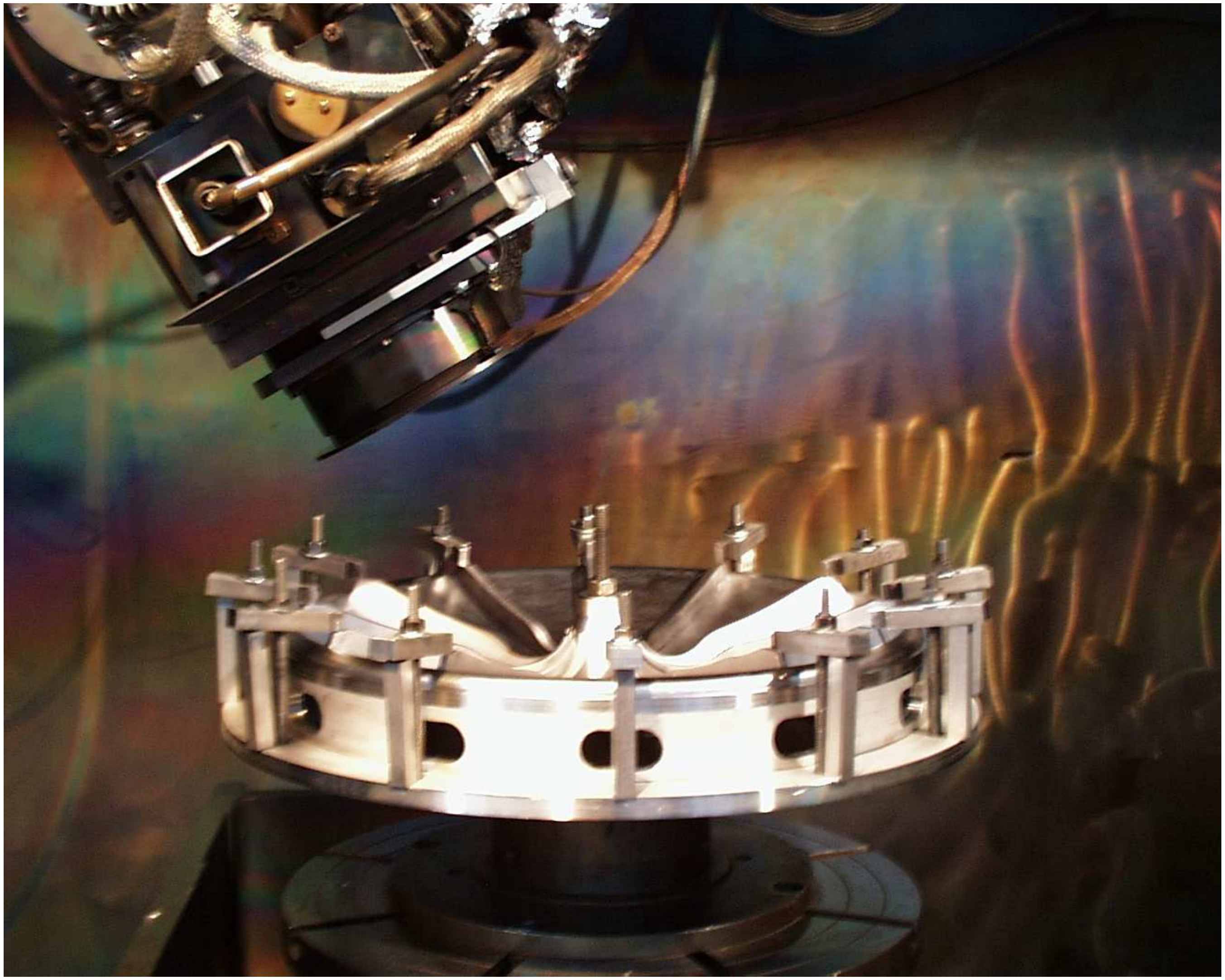
Spoke with end transition saddles and beam tube



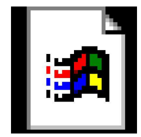
Endwall gusset fixturing



Setup for endwall gusset welds



Longitudinal seam weld on spoke



Seamweld.avi

Discussion on "RIA Project Spoke Cavity Fabrication" by Ken Shepard & Joel Fuerst

Shepard was asked, why they only do a light BCP before testing the spoke cavities. He answered that the cavity is electropolished before the final welding of the end dishes. This gives a very smooth surface which is preserved with a light BCP. Heavy BCP would reintroduce surface roughness. He believes that for the desired field levels (> 30 MV/m surface field) this might be an issue to overcome high field Q-degradation.

On the fabrication of the spoke-cavity connection Shepard explained that the flared connection is not extruded, but welded on. They felt that this would give them better geometric tolerances. They did this similar to the LANL approach for previous cavities and might reconsider, depending on discussion with LANL and Zanon. For comparable performance the LANL approach might be preferable, as it eliminates weld-steps.

On the second part of the presentation Fuerst confirmed that the cavity body is rolled from one piece and does only have one weld, this is different from LANL, that used several pieces and thus needed 3 welds.

Finally the post-treatment of welds was discussed. Shepard explained that they stopped doing any post-treatment, like machining or grinding, which is still done at other places. They feel that touching the smooth weld beads would be disruptive. They do not believe that they saw any performance penalty using this approach.

The Fabrication of the First French Spoke Prototype

J. Lesrel, CNRS, IPN Orsay

The fabrication of the first β=0.35 spoke-type cavity was recently achieved, leading us to proceed with its industrial fabrication by the French company CERCA at Romans. This talk describes the fabrication process of this cavity prototype.

Within the framework of the collaboration between FRAMATOME-ANP and the CNRS, IPN and CERCA have started a tight collaboration to build our first spoke cavity. This French company, ISO 9000 certified, is well-known for its ability in fabricating cavities.
The prototype was delivered middle July. For the fabrication we used 3 mm thick Niobium sheets (RRR>250) coming from Tokyo Denkai Co, Ltd.

All the cylinders (i.e. the beam and coupler tubes, the spoke bar and the body) are fabricated by roll-welding. Each weld is made with an electron beam welding machine under high vacuum (<10-5 mbar).

The flanges are carved directly into Niobium rod (this allows us to anneal the cavity without caring for diffusion problems into the furnace). Then, they are welded to the beam tubes.
The walls are made by spinning and the iris hole is done by extrusion. The stiffeners are welded on the beam tubes (8 grooves are made on the tubes to set precisely the supports). Then, the stiffeners-beam tubes set is welded on the wall. At last, the stiffeners are welded by spot on the re-entrant part of the wall.
The spoke bar is realised by squeezing the central part using a forging press.
After doing the beam hole, a rim-like tube is welded on the center.
Finally, these pieces are welded on the cavity body.
Before each welding, pieces are cleaned (BCP, rinsing and drying under ultra-pure nitrogen). Dimensional controls are performed on each stage of the fabrication process to control a possible buckling due to the welding. This first prototype will allow us to validate the design (with respect to electromagnetic and mechanical properties) but also the fabrication process.

Fabrication of the first French spoke prototype

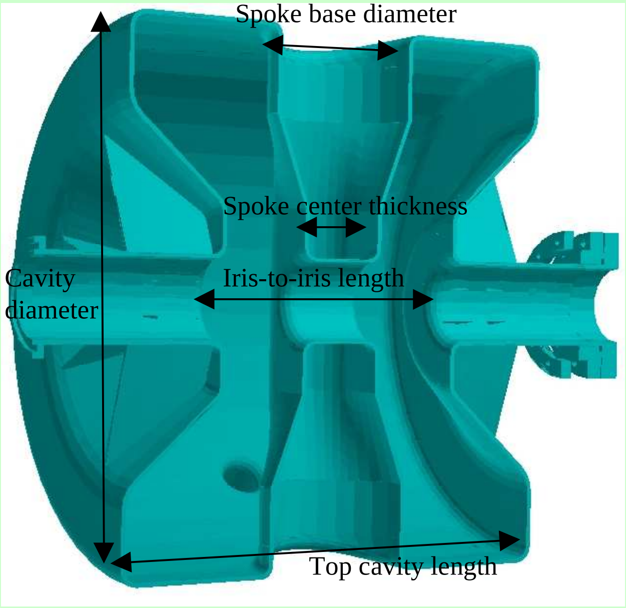
Jean Lesrel for the IPN Orsay cavity group

AMANDA $\beta = 0.35$

RF parameters

Frequency	**358.66 MHz**
Q_0 **@ 4K**	$1.9\ 10^9$
r/Q_0	$220\ \Omega$
G	$101\ \Omega$
E_{pk}/E_{acc}	**3.06**
B_{pk}/E_{acc}	**8.28 mT/MV/m**
Optimum beta	**0.363**

Dimensions



Main dimensions (in mm)	
Cavity diameter	408
Top cavity length	354
Spoke base diameter	118
Spoke center thickness	67
Spoke center width	147
Gap-center to gap-center length	150
Iris-to-iris length	200
Tube length (from iris to flange)	150
Beam tube aperture	60

Companies

Niobium: TOKYO DENKAI (Japan)

RRR 250 thickness: 3 mm

Cavity fabrication : CERCA (France)

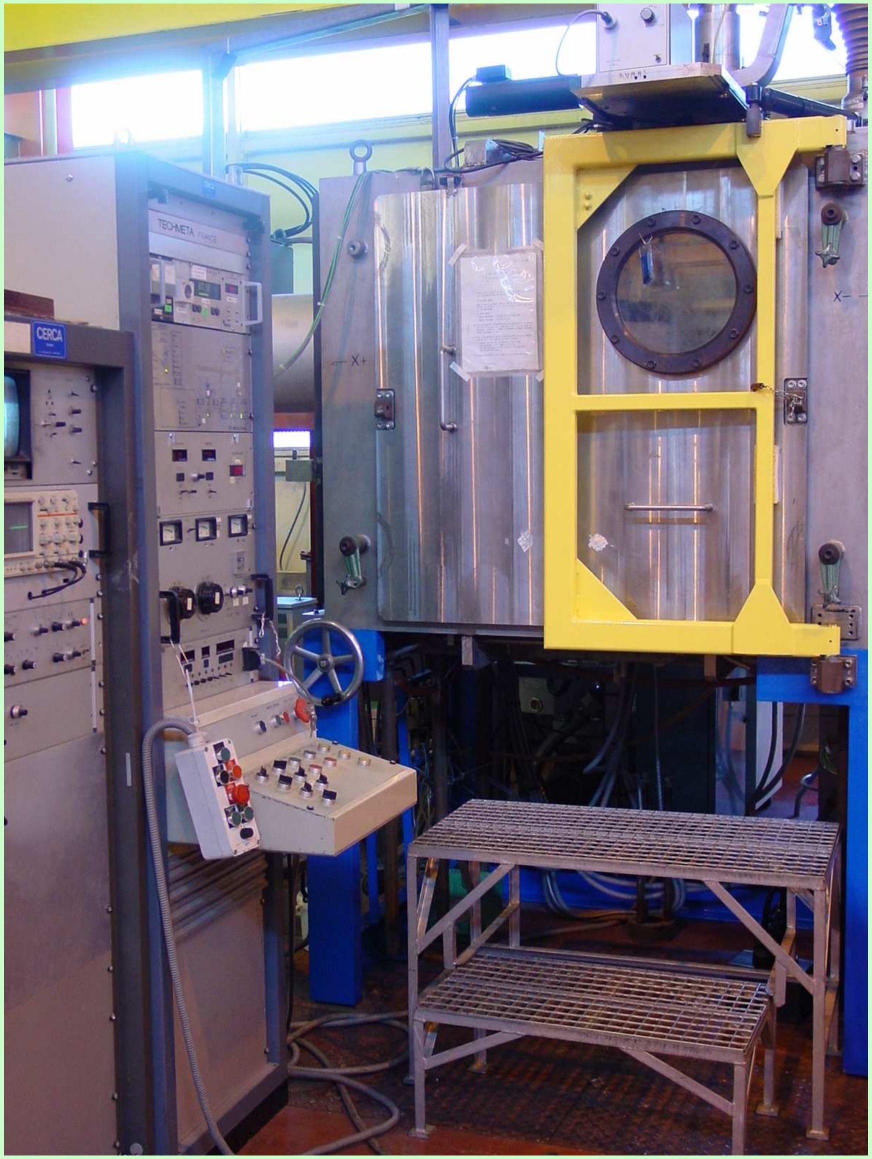
Fabrication time: 5 months

Subcontractors:

Spinning : BONITEMPO (France)

Machining : PRECISION MECANIQUE DUC (France)

Electron Beam Welding Machine



Vacuum < 10^{-5} mbar

Diameter 1.5 m

Length 4.5 m

Beam power 6 kW

Before welding

Chemical cleaning

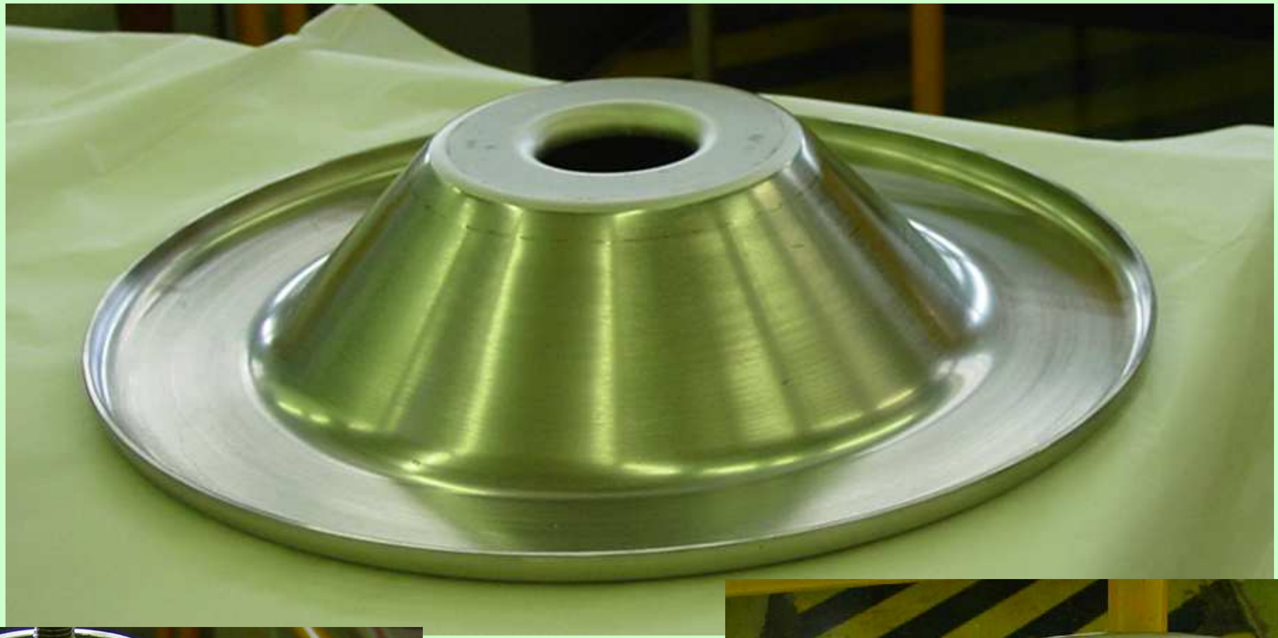
degreasing

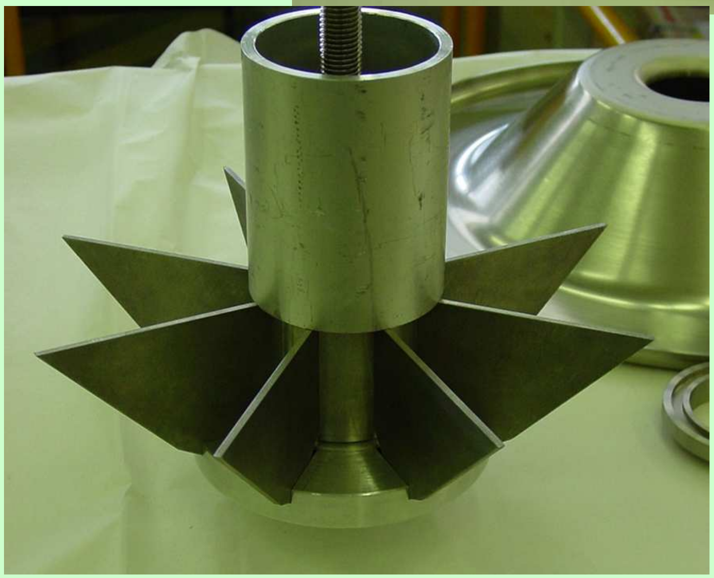
rinsing

Drying under Nitrogen atm.

Fabrication method (cylinders and flanges)

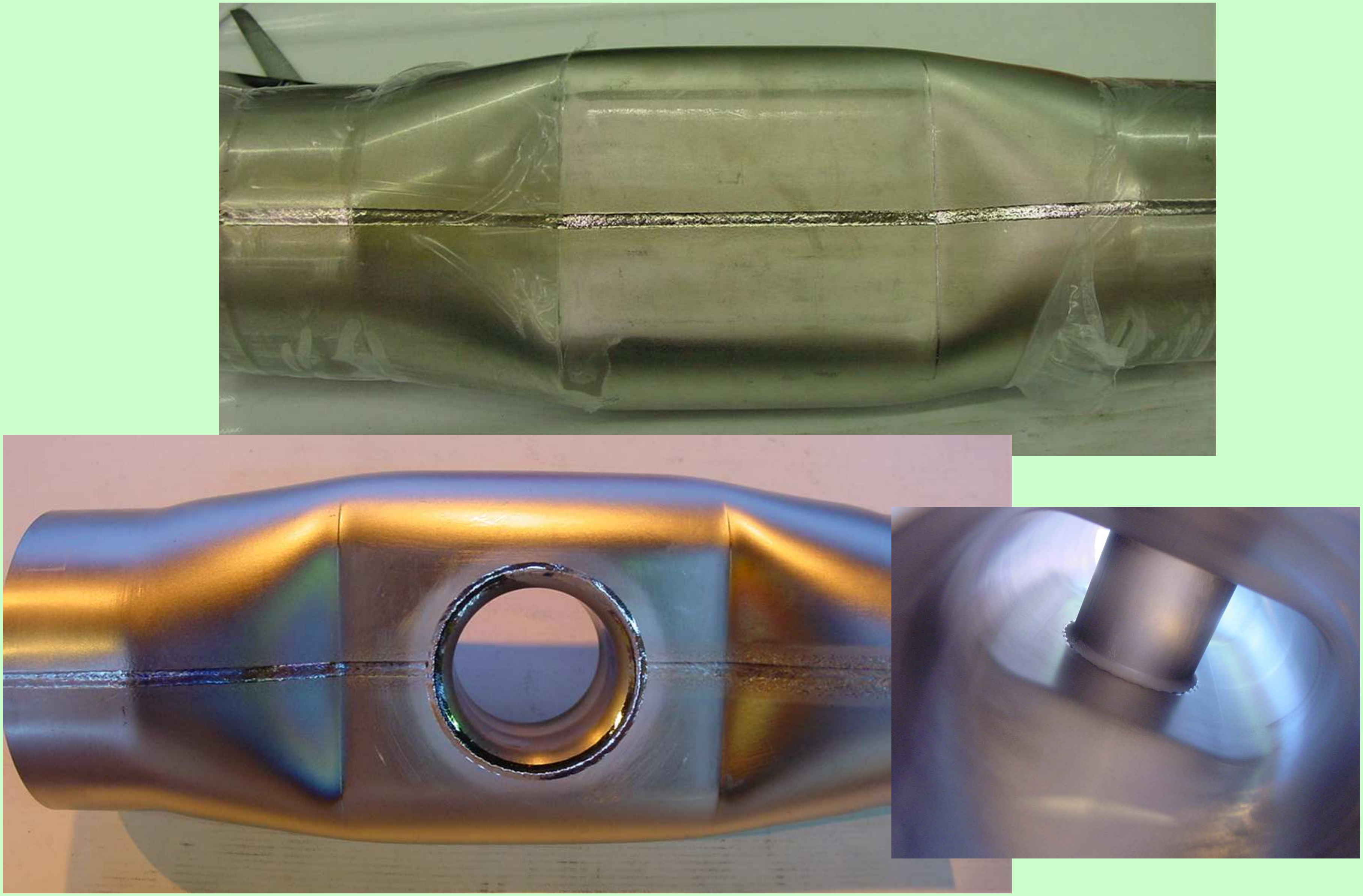
Fabrication method (walls and stiffeners)



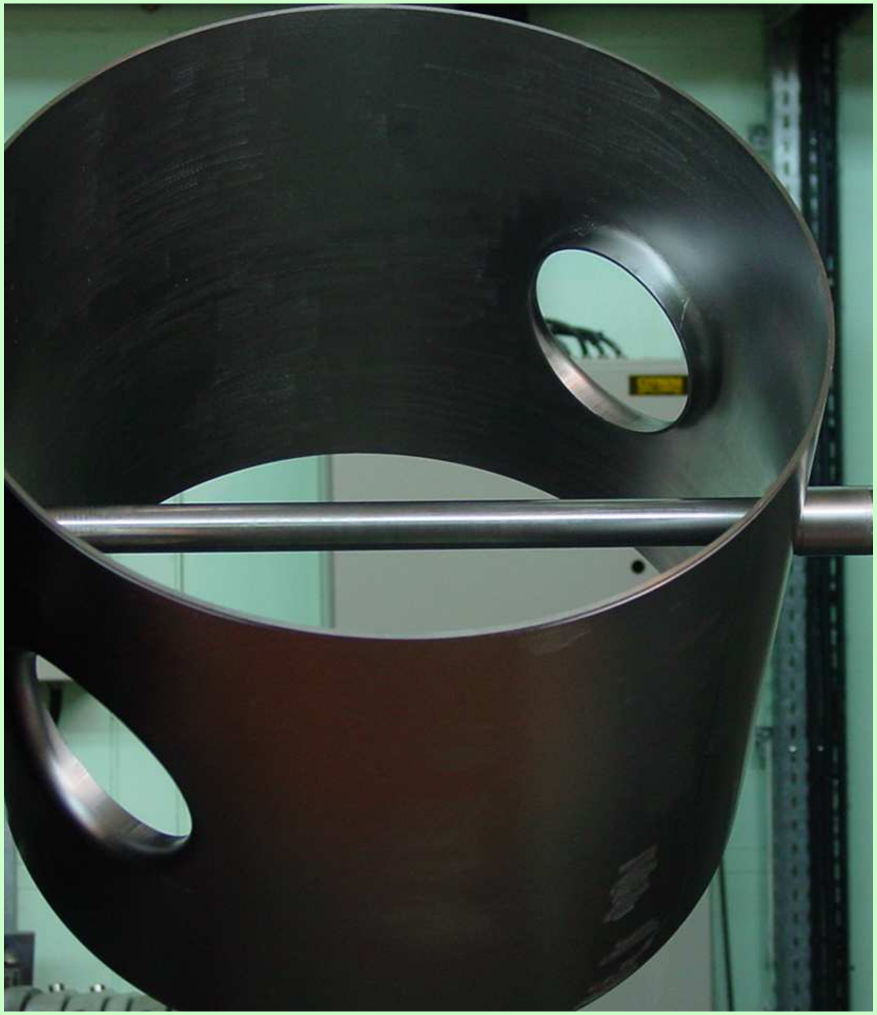


Fabrication method (walls and stiffeners)

Fabrication method (spoke bar)



Fabrication method (cavity body)



Fabrication method (final assembly)

Dimension control

	calculated sensitivity	dimension	measured	frequency variation
Cavity diameter	-950 kHz/mm	414 ± 0.2	413.9	+ 95 kHz
Spoke base diameter	+650 kHz/mm	118 ± 0.1	117.8	- 130 kHz
spoke center width	-800 kHz/mm	147 ± 0.2	146.8	-160 kHz
Spoke center thickness	-600 kHz/mm	67 ± 0.1	67.2	+ 120 kHz
top cavity length	+450 kHz/mm	360 ± 0.5	361	+ 450 kHz
			Total	+375 kHz

Calculated frequency : **358.55 MHz**

Measured frequency : **358.85 MHz**

Δf=300 kHz

Mechanical tests at room temperature

Tuning sensitivity: 500 kHz/mm

Structure spring constant: 2600 N/mm

Frequency variation under vacuum:

100 kHz

Frequency variation at 4 K:

in November

Discussion on "The Fabrication of the First French Spoke Prototype" by Jean Lesrel

Details of the Orsay design were discussed. Lesrel clarified that the frequency variation from air to vacuum was quoted per atm and included vacuum loading and dielectric effects. The cavity stiffening is self-supporting and no extra support is needed to put the cavity under vacuum.

The spoke fabrication itself was discussed next. A spoke cylinder was welded from two pieces, then the flat part at the aperture was formed by squashing. The weld is positioned to go across the center of the beam hole. The reason is the location of the highest electric fields that are on the outside curvature of the spoke racetrack. Delayen commented that for an optimized spoke the electric field in the center plane should be constant around the circumference of the spoke. To add the spoke to the cavity, the cavity body is deformed to slip the spoke from inside into its proper position, then the connection is fully welded from the outside.

In a next topic the flanges of their spoke resonator were discussed. The cavity and all flanges are made from niobium and indium seals are used at the flanges. The reasoning behind that was elimination of more complex handling of the prototype. Lesrel and Junquera explained that the BCP by dumping the cavity into a bath might cause problems at the brazes of other flanges. Schrage argued that CERCA, the fabricator of that spoke cavity, delivered elliptical cavities to LANL that had brazes for stainless steel flanges and there were no problems seen in LANL’s flow-through BCP. He suggested not to do BCP by dumping the cavity into a bath, as this reduces wall thickness twice as fast as regular BCP. Bousson replied that this scheme will only be used for the first BCP of the first prototype cavity, subsequent dumps will only be done from the inside, as the system to do that is not ready yet.

Shepard pointed out that designs using brazes need to pay attention to remelt problems, if subsequent welds need to be done close to a braze joint. They had to address this for the helium vessel fixtures on their 2-spoke resonator.

Asked about their future plans for flanges, Junquera explained that they intend to go to the TESLA flange design using an aluminum gasket. Schrage pointed out that this design seems to need more understanding and that the copper gasket used for all LANL cavities turned out to be a very robust seal.

As a last topic potential risks due to a ring attached to the stiffening ribs were discussed. It turned out that the ring was a design option that is not needed for future cavities. Also it does not present a danger of a trapped gas volume, as there is a gap between the ring and the resonator endwall. It was not clarified, if the ring was needed to hold the stiffening ribs in place for welding.

Fabrication of the AAA β = 0.175 Spoke Resonator

Dale Schrage, LANL

The fabrication of the β = 0.175, 2-gap, 350 MHz spoke resonator cavities for the LANL Advanced Accelerator Applications (AAA) Program was carried out in industry in collaboration with INFN/Milano. The vendor, E. Zanon, S.p.A., delivered the two cavities slightly ahead of schedule on the 10th month procurement. Some of the design details and many of the details of fabrication were left to the vendor; these are discussed. The project schedule is presented. Lastly, there is discussion of things that will be done differently for the next procurement.

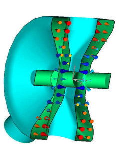
LA-UR-02-6141

FABRICATION OF THE AAA β=0.175 SPOKE RESONATOR

Dale Schrage
LANL

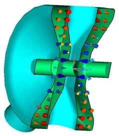
Workshop on the Advanced Design of Spoke Resonators

Los Alamos, NM, USA
October 7 and 8, 2002



CAVITY PROCUREMENT

- **Cost Competitive Procurement**
- **Wrote SOW & Procurement Package**
- **Solicited “interest” from**
  - **4 US Vendors - one interested**
  - **3 European Vendors - three interested**
  - **3 Japanese Vendors - none interested**
- **Awarded to Lowest Bidder**



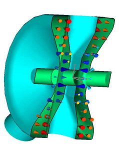
LA-UR-02-6141

PROCUREMENT PERSONNEL

- **Cavity Statement of Work: Richard LaFave**
- **Cavity Procurement Agent: Frank Targhetta**
- **Liaison Support & Collaboration: INFN/Milano**
  - **Danilo Barni**
  - **Angelo Bosotti**
  - **Carlo Pagani**
- **Vendor: E. Zanon, S.p.A**
  - **Project Engineer: Giorgio Corniani**
  - **Lead Technician: Mauro Festa**

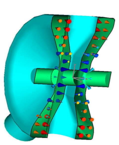
SCHEDULE

TASK	START DATE	COMPLETE DATE
ADTF LINAC REVIEW	4/10/01	4/12/01
CAVITY PHYSICS DESIGN	4/15/01	6/15/01
POWER COUPLER CONCEPT	4/15/01	6/15/01
CAVITY STRUCTURAL DESIGN	5/15/01	6/15/01
PROCUREMENT DOCUMENTS	5/15/01	7/1/01
BID PERIOD	7/11/01	8/3/01
AWARD	8/3/01	8/29/01
CAVITY FABRICATION	9/1/01	7/11/02



FABRICATION OF SPOKE

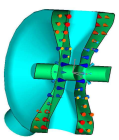
- **TWO OPTIONS:**
- **OPTION A: STAMP HALVES AND SEAMWELD**
  - **STRAIGHTFORWARD FORMING OPERATION**
- **OPTION B: FORM FROM TUBE**
  - **SOME PROTOTYPING REQUIRED**
- **VENDOR OPTION, CHOSE OPTION B**



LA-UR-02-6141

SPOKE/CAVITY JOINT

- **TWO OPTIONS:**
- **OPTION A: STRAIGHT JOINT**
  - **SIMPLER TOOLING**
  - **MAY BE DIFFICULT FOR > 1 SPOKE**
  - **AAA β = 0.175, ANL β = 0.29 & 0.40, 2-GAP**
- **OPTION B: FLARED JOINT**
  - **EASIER INSERTION**
  - **MORE COMPLEX TOOLING**
  - **ANL/RIA β = 0.34, 3-GAP**
- **VENDOR OPTION, CHOSE OPTION A**



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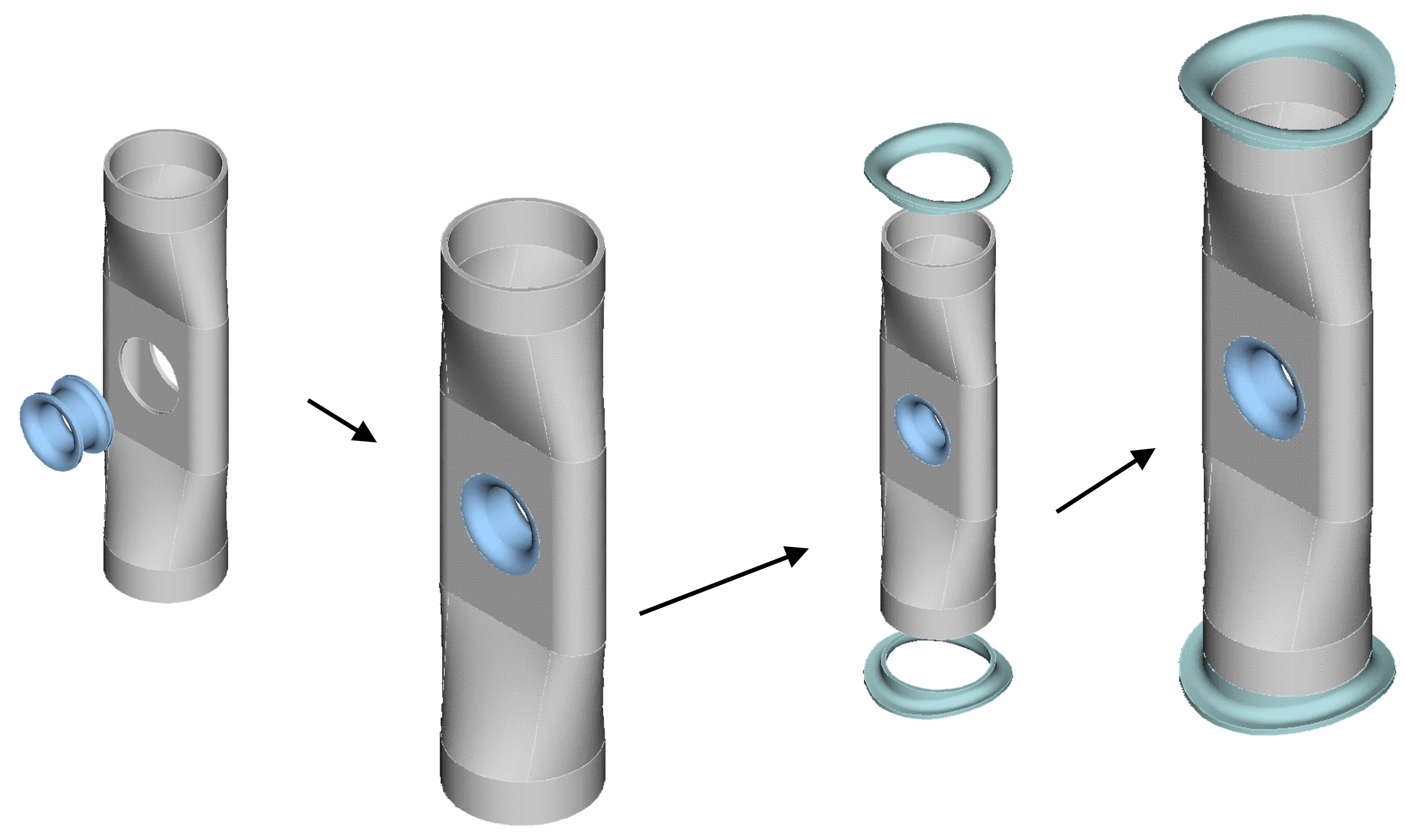
OPTION B (Courtesy of AES)



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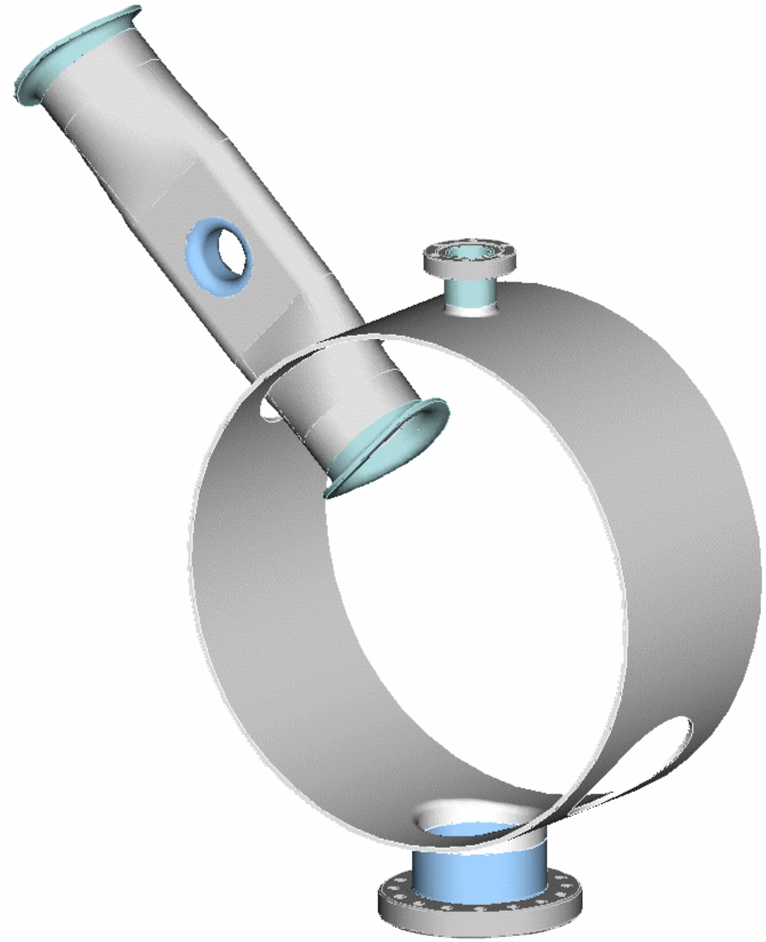
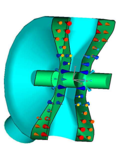
OPTION B (Courtesy of AES)



Los Alamos NATIONAL LABORATORY

THINGS TO DO DIFFERENTLY

PROVIDE NIOBIUM	WE DID
VISIT FREQUENTLY	INFN DID
PROVIDE FLANGES	NEXT TIME
PROVIDE FASTENERS & TOOLS	NEXT TIME
UNIFORM THICKNESS WELDS	NEXT TIME
SPECIFY CARRIER & TYPE	NEXT TIME



Discussion on "Fabrication of the AAA β=0.175 Spoke Resonator" by Dale Schrage

The discussion started with the comparison of methods to insert spokes into the cavity body. Shepard suggested to make the choice dependent on the achievable alignment tolerances, especially for multigap spoke resonators, where the alignment of succeeding beam holes is an added complexity. Schrage pointed out that the importance of this issue depends on the beam-current and thus the related aperture size. Tolerances should not be over restricted, if cost is an issue.

The rest of the discussion focused on the issue of niobium sheet quality. The niobium sheets that LANL used for APT and AAA in recent years came from three different vendors. They all were only inspected by dumping into DI-water and by visual inspection. Zanon redid the visual inspection when they were provided with the niobium for the LANL spoke resonators. Eddy current methods, like used by TESLA are not available in most places. LANL is well aware of the risk taken by limiting inspections to the two steps mentioned. In the future eddy current testing might have to be added to the QC plans.

Pagani mentioned that for TESLA rejections of sheets due to eddy-current inspections have dropped over the years, as vendors became more experienced in avoiding contaminations in the materials. He also pointed out that for the very high fields in TESLA (up to 50 MV/m peak surface fields) the results of these inspections are not relevant anymore to detect problematic defects. While eddy-currents can detect defects down to 100 μm, at these high fields much smaller defects are already performance limiting. Shepard pointed out that materials are handled in many steps and there can never be too much testing. Especially a 48 hour dump into DI-water at an early stage can identify fabrication issues.

Cavity Processing

Mike Kelly: "*Surface Processing of Spoke Cavities for RIA*"
(Abstract | Viewgraphs | Discussion)
Sebastien Bousson: "*Processing of the First French Spoke Cavity*"
(Abstract | Viewgraphs | Discussion)
Tsuyoshi Tajima: "*Preparation Procedures for Testing the LANL/AAA Spoke Cavities*"
(Abstract | Viewgraphs | Discussion)

Surface Processing of Spoke Cavities for RIA

M. Kelly, Argonne National Laboratory

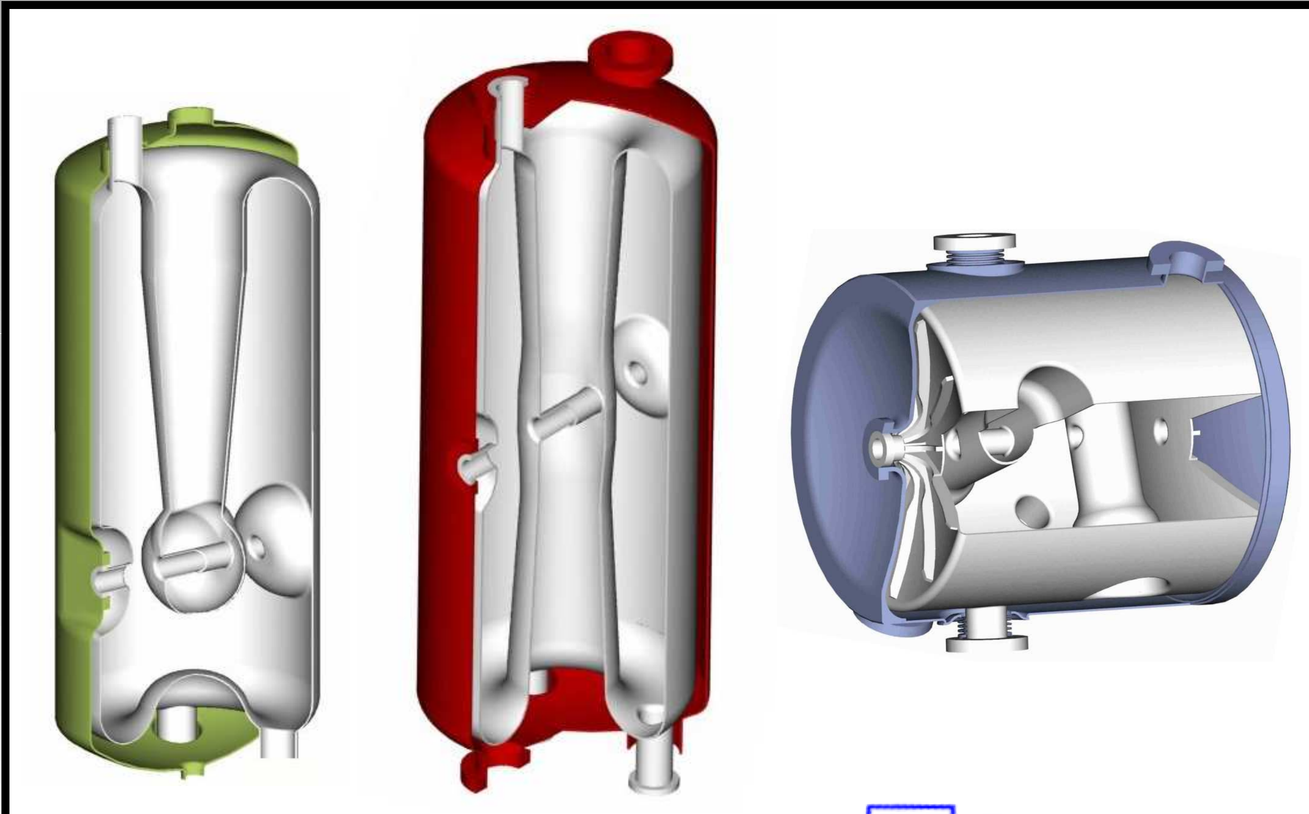
Surface processing, handling and high-field test results (Eacc>10 MV/m) of the ANL beta=0.3 and beta=0.4 single-cell RIA prototype spoke cavities will be reviewed.

Initial processing of the 2-cell spoke prototype for RIA including a heavy electropolish of the critical rf surfaces is also discussed.

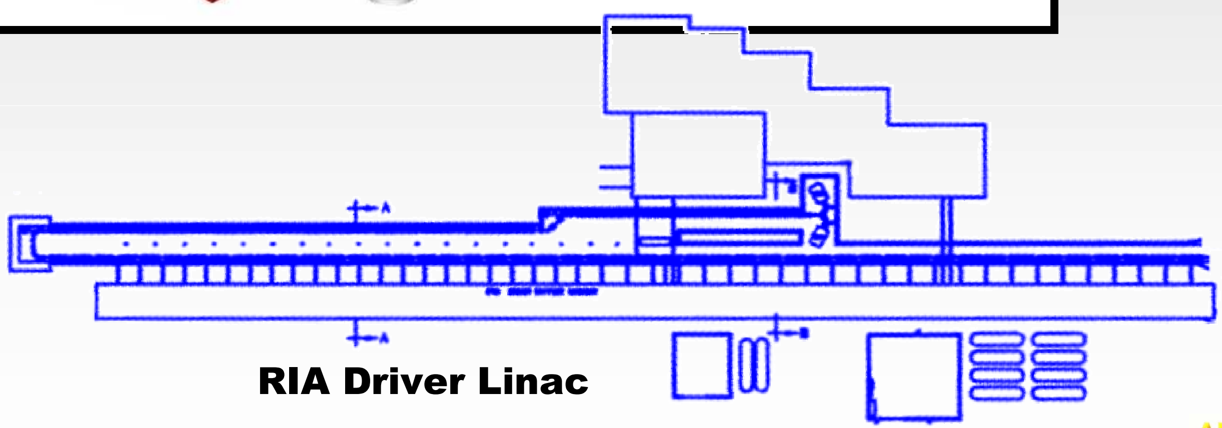
Surface Processing of Spoke Cavities for RIA

M.P. Kelly
K.W. Shepard
M. Kedzie
J.D. Fuerst

Higher gradients in drift-tube cavities for RIA

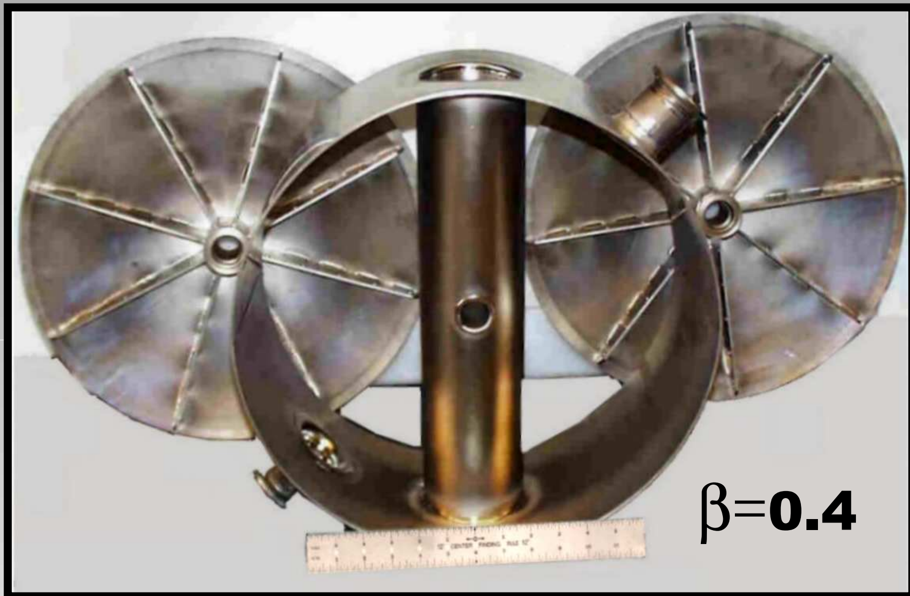


- Cost and Performance
- Clean processing techniques for drift-tube structures
- Developed for TESLA and at JLAB for elliptical cell cavities
- Recent progress related to drift-tube cavities



RIA Driver Linac

ANL β=0.3 and β=0.4 Prototype Spoke Cavities for RIA



- **Constructed in 1996-97**
- **Single-cell 350 MHz solid niobium**

- **Electropolished**
- **Electron-beam welded**
- **Light chemical polish**
- **BCP and HPR**

See Delayen et al, SRF 1993, for discussion of 805 MHz spoke

A Two-cell β=0.4 Spoke Cavity for RIA


Completed: 100-200 μm removed

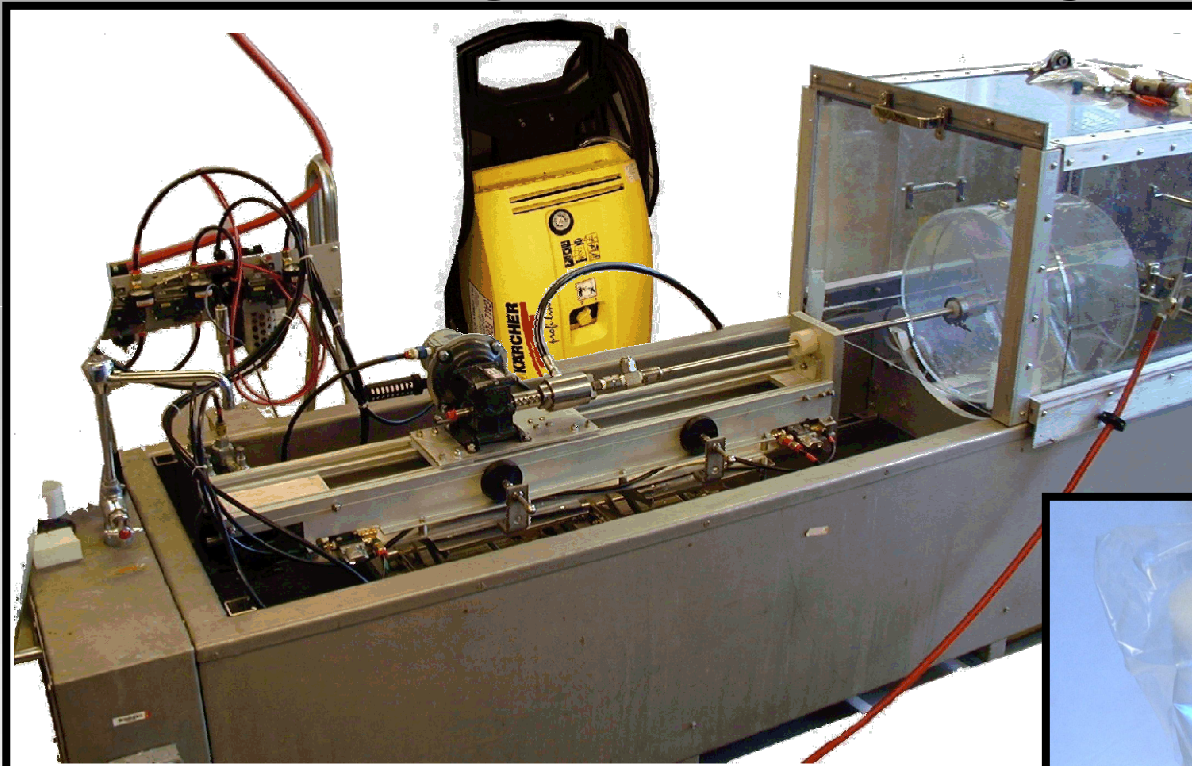
- 345 MHz
- Solid niobium, 3.175 mm RRR$\geq$250 sheet
- Plan for Surface for Treatment: Heavy EP, HPR, e-beam Closure Weld, Light BCP, and HPR

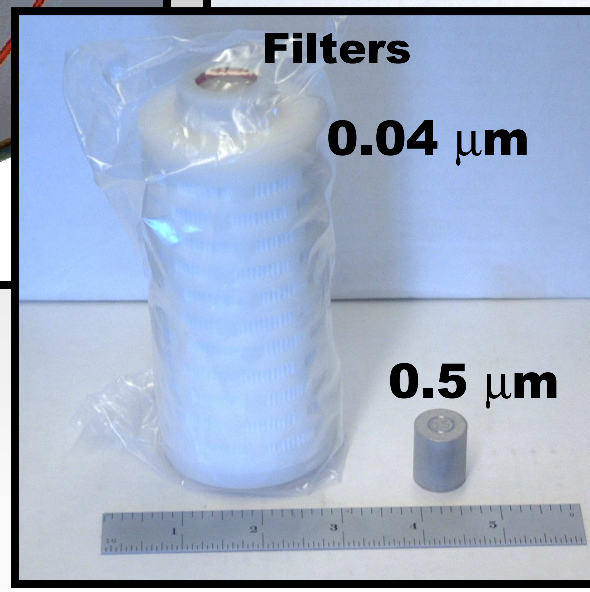

As of Sept 20: 25 μm removed

ARGONNE NATIONAL LABORATORY • UNIVERSITY OF CHICAGO

ANL Physics Division

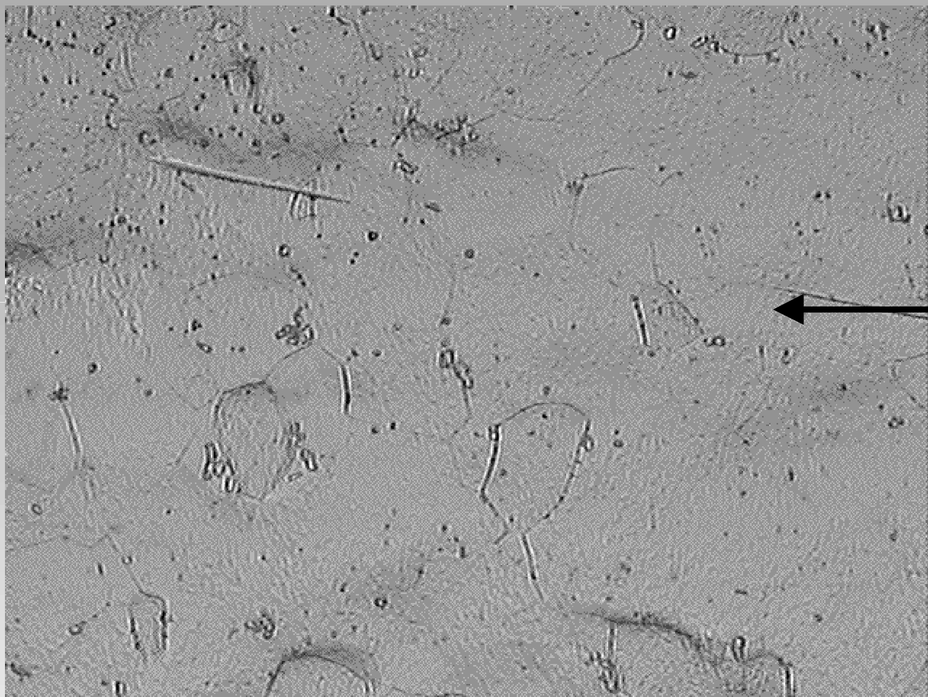
ANL Drift-Tube Cavity Surface Processing: An Automated High-Pressure Rinse System





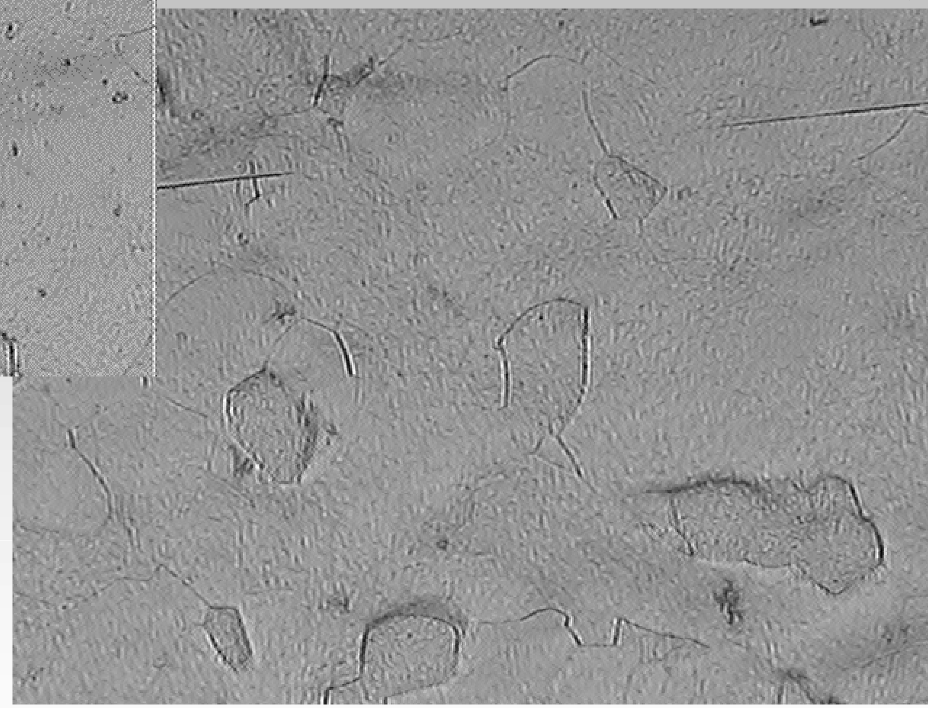
- PC controlled
- Ultra-pure DI water
- 20 l/m, up to 3000 PSI (1750 PSI)
- 0.04 μm filtration
- Curtained clean room area

Electropolished Nb surface Before and after HPR at 1750 PSI



Cleaned with ethanol and Acetone, before HPR

240 μm



After HPR

High-Pressure Rinse System: Manufacturers

High-pressure filtratration

•Domnick-Hunter PROPOR PES 0.04 μm,
housing product #VIL01ABN-HP 4350 PSI

•Swagelok filter SF-8F-K4-05, housing SF-6TF2-LE

•Plumbing: Swagelok 8R nylon bore, 4000 PSI

High-pressure Pump

•Karcher HD1090 3000 PSI, 4 GPM

Translation carriage, nozzles:

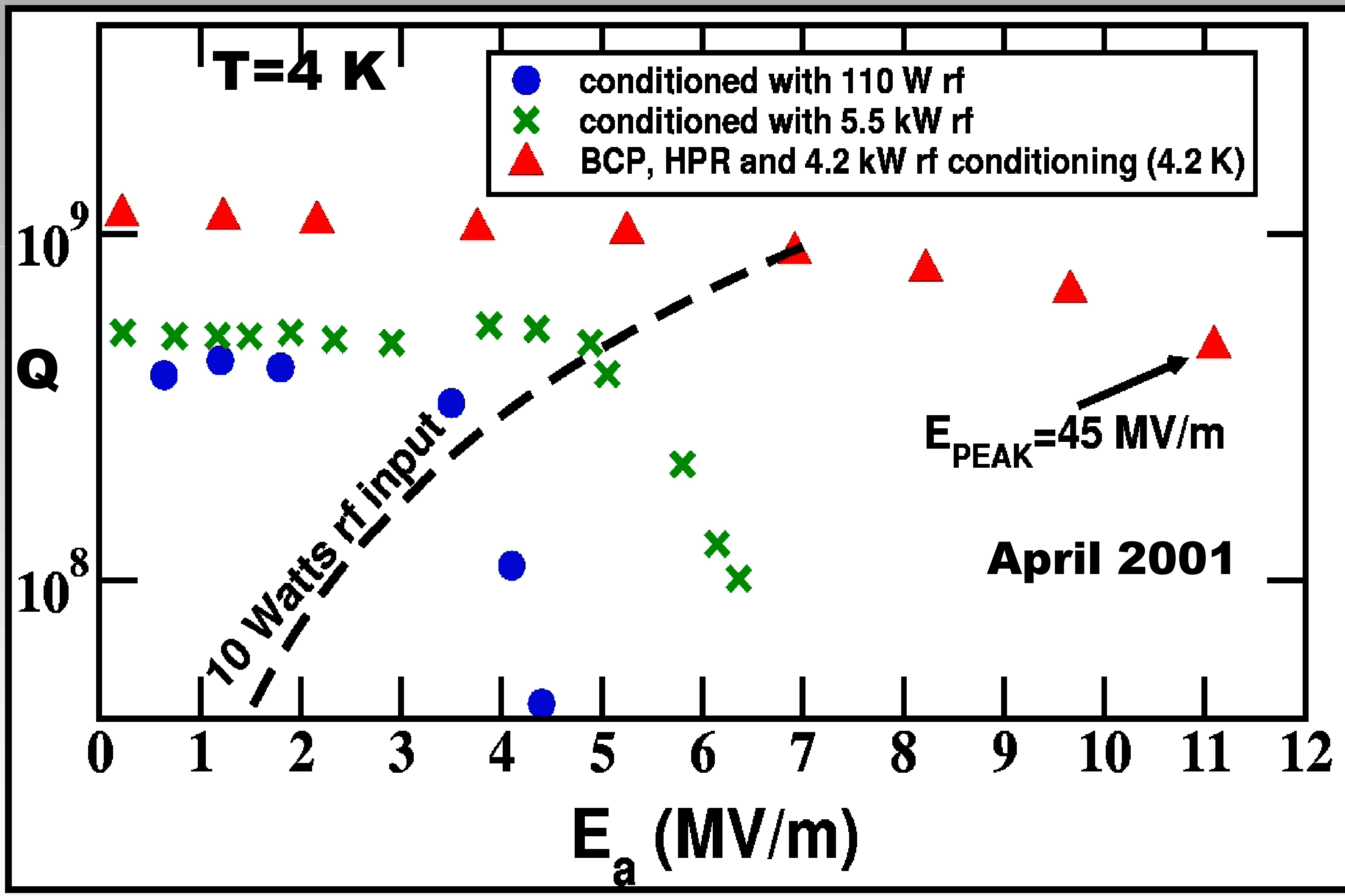
•StoneAge Waterjet Tools (CAVQ custom lancing system)

•Nozzles TD-010-P4

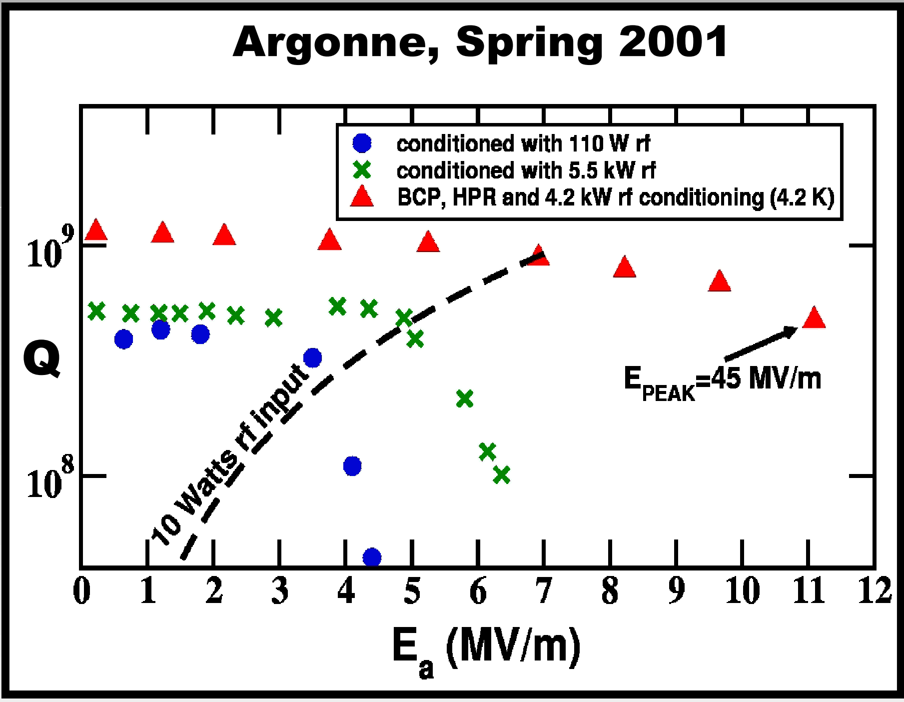
A Manual High-Pressure Rinse

Used for:
- **Cleaning after EP**
- **Prior to e-beam weld**
- **Coupler parts, bagged and assembled downstairs**

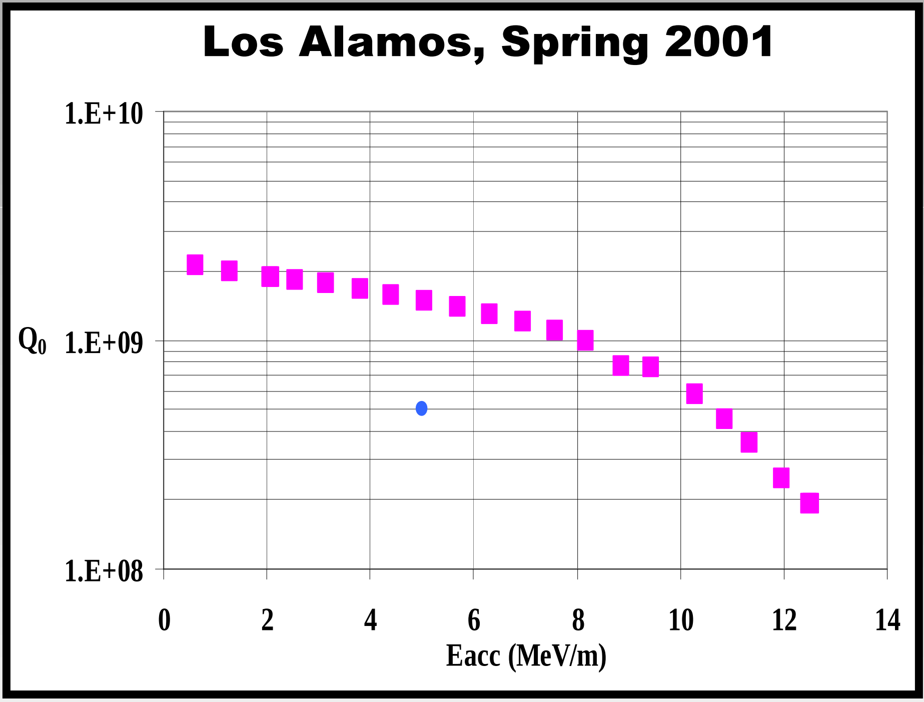
ANL β=0.4 Prototype Spoke Cavity Test Results



ANL β=0.3 and β=0.4 Prototype Spoke Cavity Results

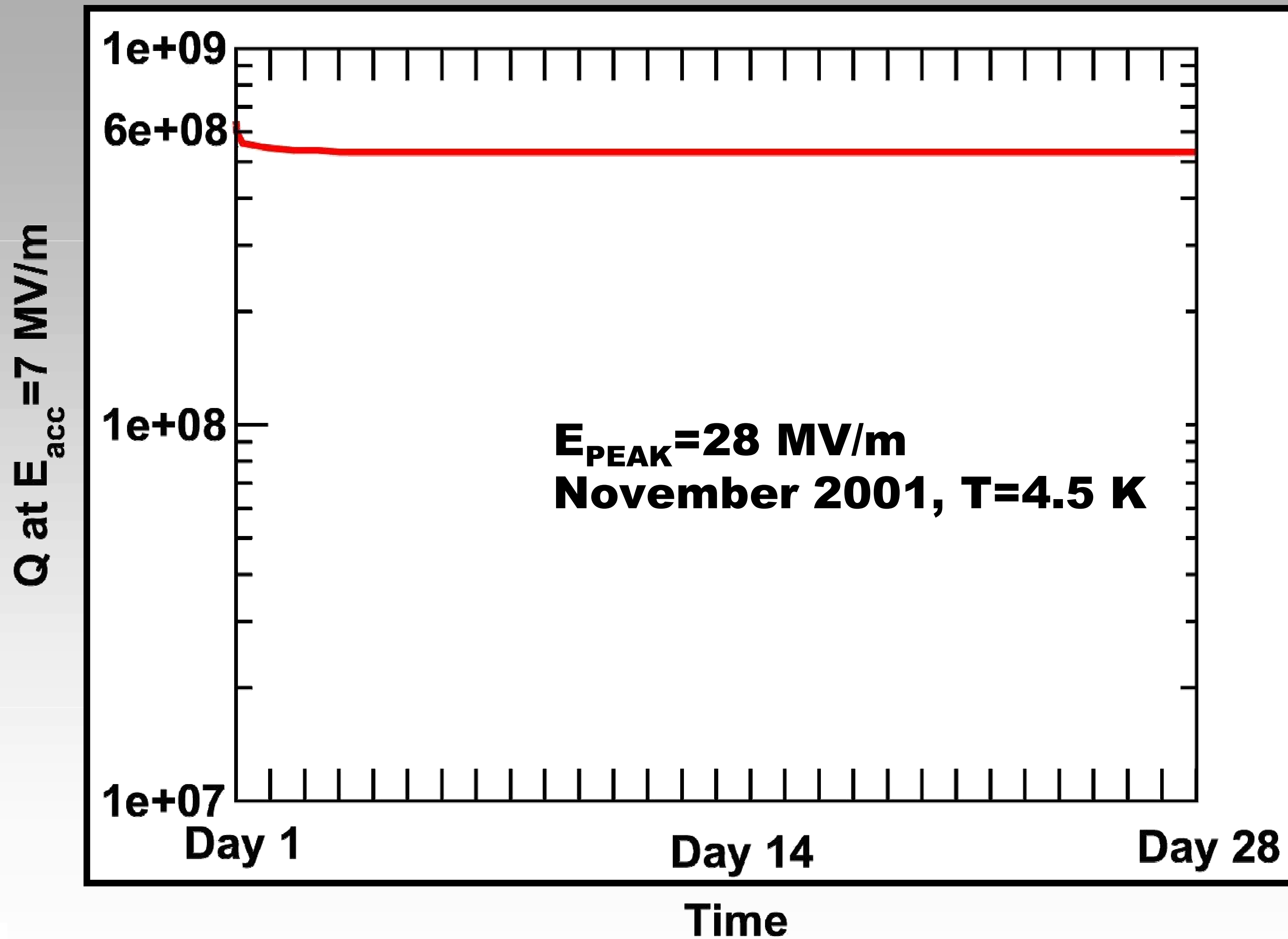


Argonne Result β=0.4 cavity



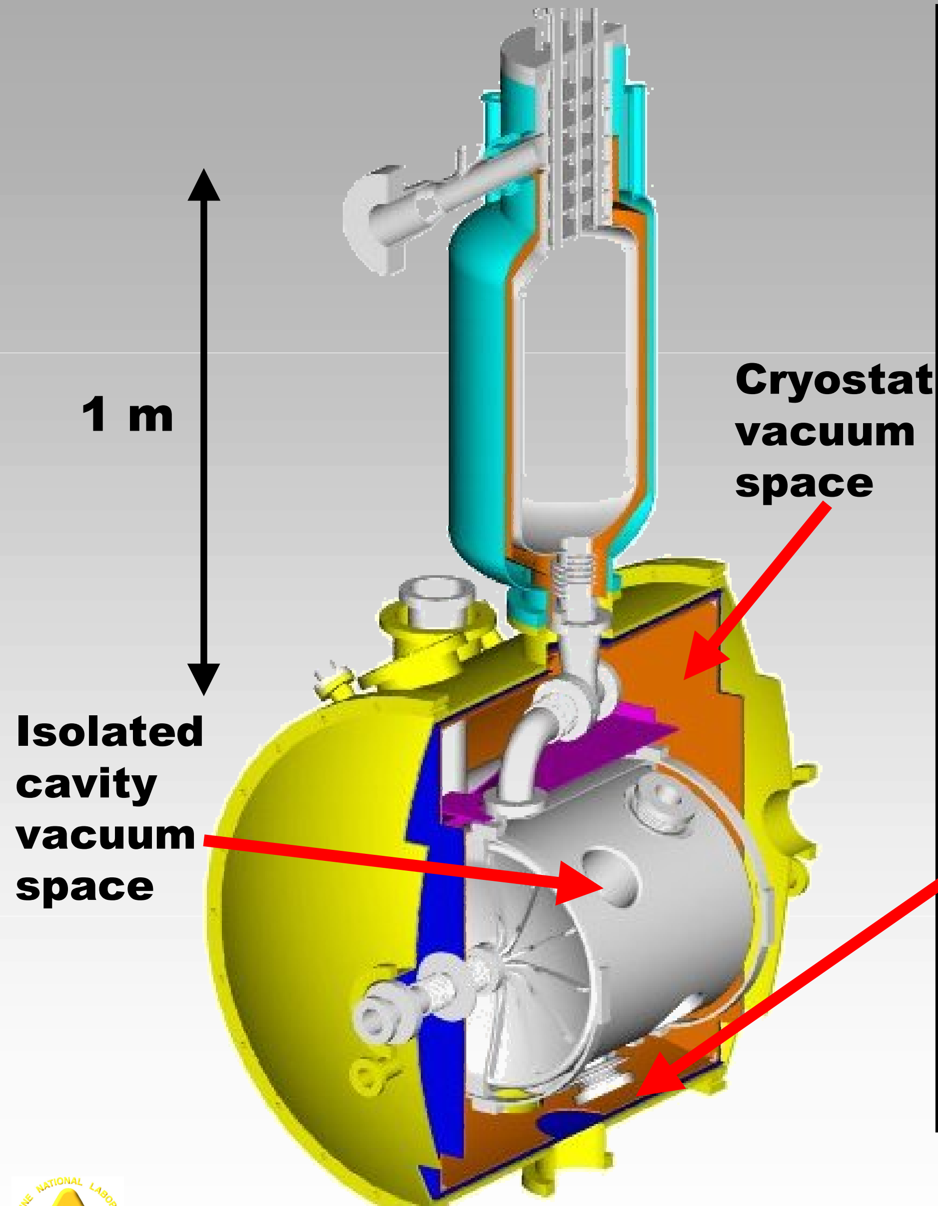
Los Alamos Result β=0.3 cavity

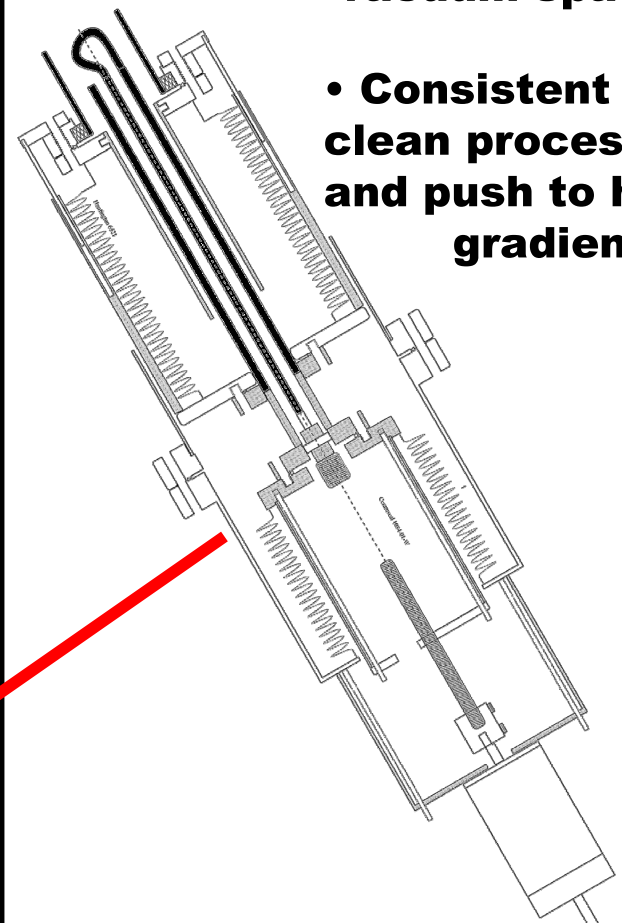
ANL β=0.4 Spoke Cavity at 7 MV/m for One Month



ANL Physics Division

Tests of 345 MHz Two-cell Spoke Cavity





Power Coupler

- Separate vacuum space
- Consistent with clean processing and push to higher gradients.

Tests of 345 MHz Two-cell Spoke Cavity

- Cavity space sealed in clean area
- ATLAS refrigerator for long-term tests
- New rf coupler, phase stabilize
- Vibration damping mount

Surface Processing of Two-cell Spoke Cavity: Electropolish

Siemens
- 89.5% by vol. of H_2SO_4 (96% conc. by weight)
- 10.5% by vol. of HF (40% conc. by weight)

- 76 liters - housing, 15 liters - end plate 50-100 cycles
- Power supply voltage: 19 V
- Power Supply On/Off → 60 sec./90 sec. ("one cycle")
- Acid Temperature: 31.5°C +/- 0.25°C
- Recirculate acid only during Off time
  20 liters/min pumped

Surface Processing of Two-cell Spoke Cavity: Electropolish

Housing Electrode

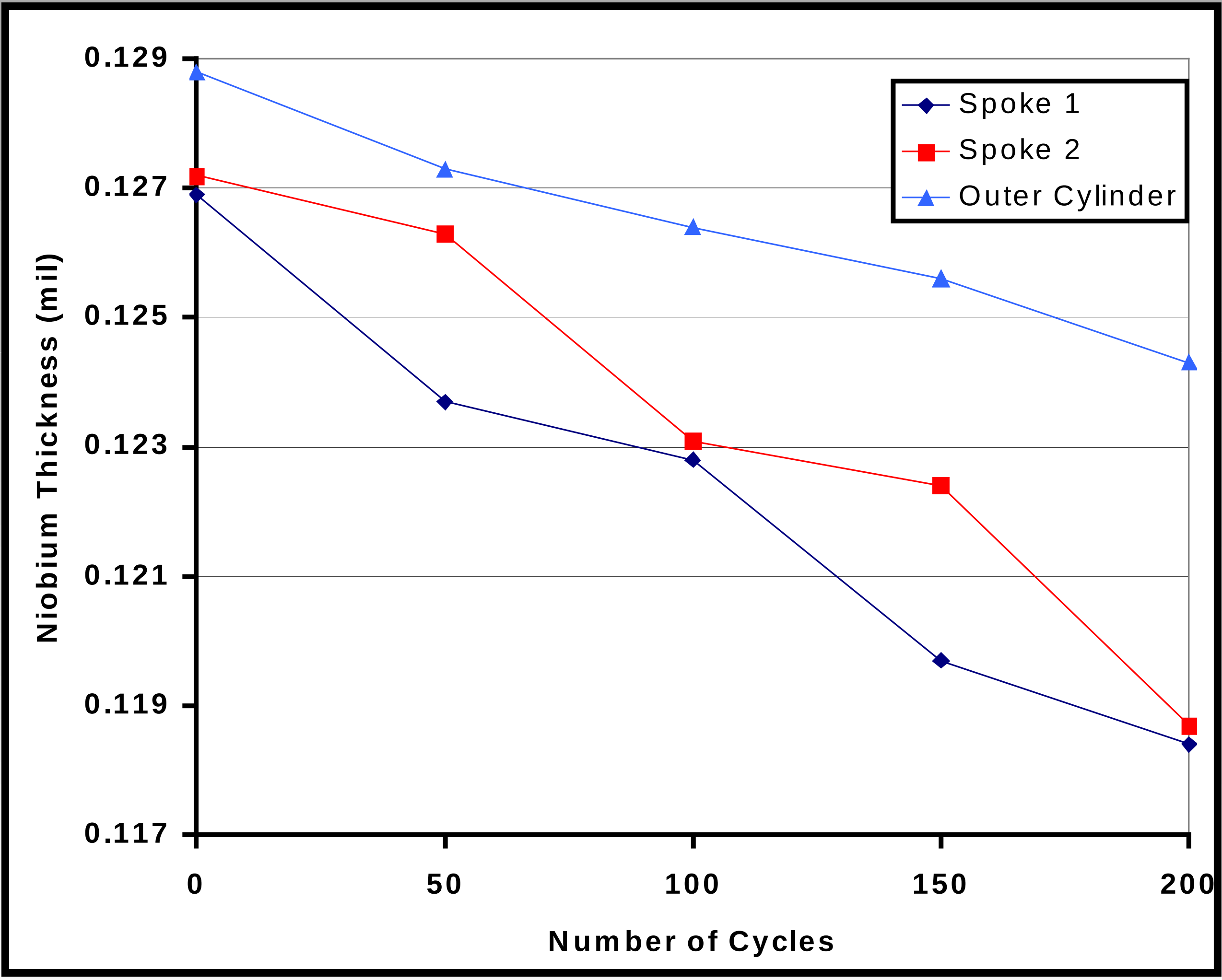
3/8" 3003 Al tubing

- **Housing area: 8600 cm^2**
  Cathode area: 4300 cm^2

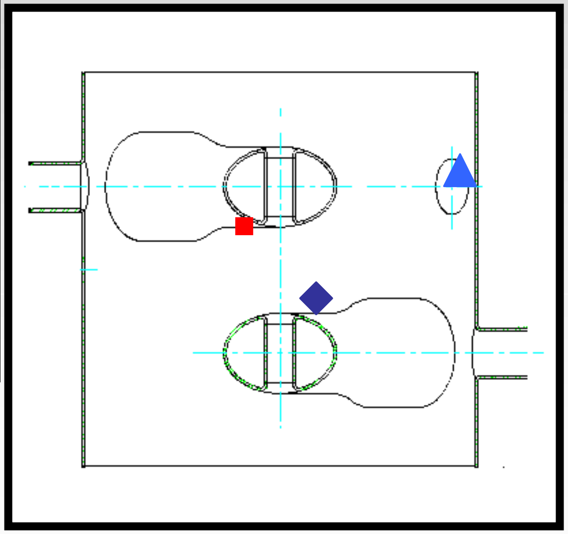
- **Endplate area: 1650 cm^2**
  Cathode area: 2110 cm^2

End Plate Electrode

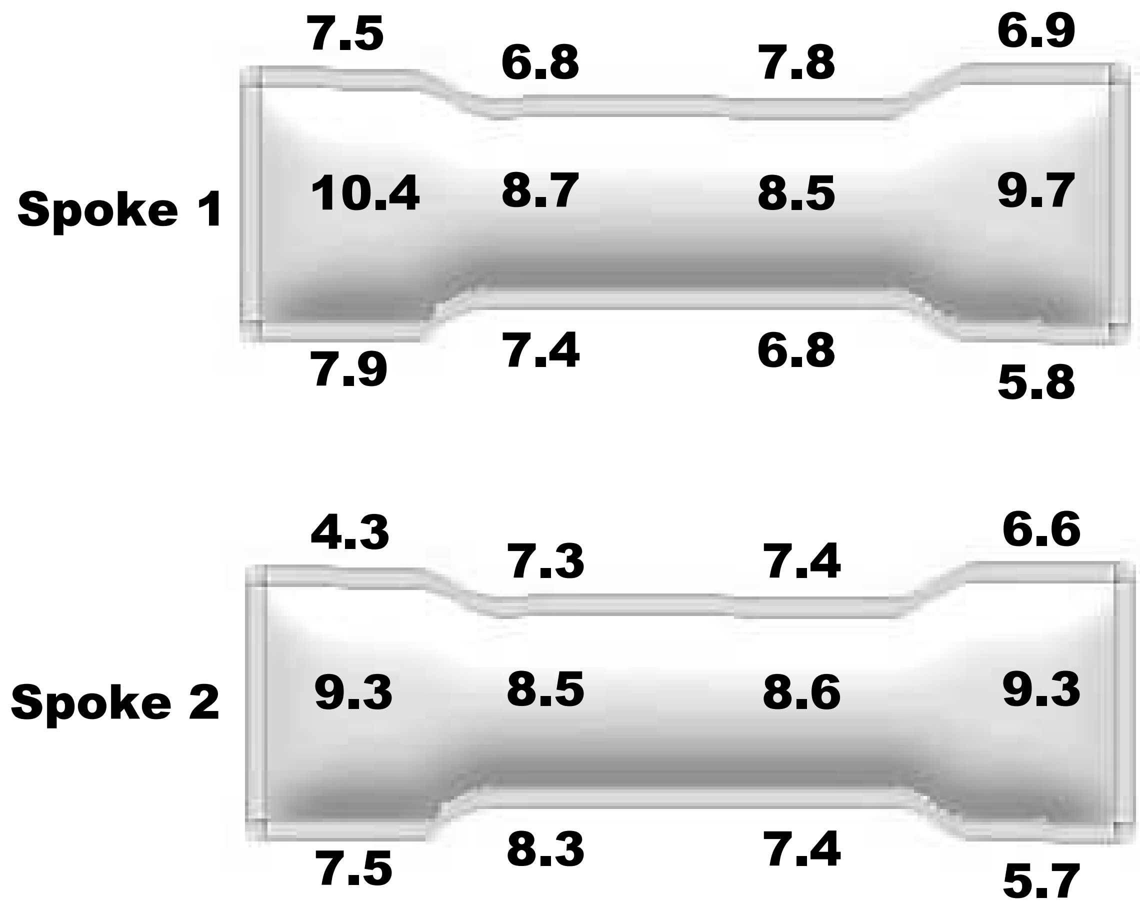
Surface Removal Rates on the Spokes and Outer Housing



- **Housing flipped after each 50 cycles**
- **Clear difference between upward and downward facing surfaces**



Total Thickness Niobium Removed (mil)



Outer Cylinder Average 4.4 mil

Discussion on "Surface Processing/Testing of Spoke Cavities for RIA" by Mike Kelly

Kelly presented Q vs E data that showed a surprising improvement of the low level Q just by high pressure rinsing. Pagani and Facco commented that this shows that localized non-BCS related losses were removed. A possible source could be residue from chemical polishing.
Kelly also presented a change in their vacuum system approach. While for their single spoke tests they had a common cryostat and cavity vacuum (like in ATLAS), for the new multispoke cavities they intend to switch to separate vacuum for the cavity and the cryostat. They have three ports available on the new cavity. Tajima suggested that from the contamination point of view it would be advisable to use a bottom port for pumping.
The power coupler used for testing the new multigap spoke resonator is not identical with the final coupler for the accelerator. Nevertheless, it has some important features of the final coupler that are demonstrated on this model.
The rest of the discussion focused on electropolishing in general and in the ANL multigap spoke resonator. Delayen asked about the effects of the hydrogen gas that is created in the polishing process. Kelly pointed out that the cavity is wide open during the polish, as the endcaps are not welded yet, so the H_2 can escape. He agreed that orientation is important to avoid trapping of hydrogen that could end up in the niobium surface. He further clarified that the electropolish process happens in about 200 steps. During each step the cavity/electrode-system is stationary. Every 50 cycles the cavity orientation is flipped to have a more even polishing effect. The polish is only done on the inside of the cavity, to maintain the overall material thickness.
Kelly reported that the downward facing surfaces are polished faster than the upward facing ones, this led them to the change in cavity orientation every 50 cycles.
There are contradictory observations on details of the EP process. Tajima and Pagani reported that KEK/TESLA have seen a clear distance effect to the electrode that determines the speed of the polishing. The irises are polished more strongly than the equator regions of their cavities. Also, both slowly rotate their cavities during the polishing procedure. Kelly reported that they observed (and found published in the literature) that the distance to the electrode is of lesser importance. The polish and its speed is determined by the boundary layer to the surface. The boundary layer must not be disturbed to maintain the layer, thus any agitation of the liquid during a polishing cycle should be avoided. Kelley asked if the"stationary"bath does work better on the downward facing surfaces due to a slow gravity-driven circulation. The issue was not resolved and needs further investigation.
As the EP process gives smoother surface, it was pointed out that polishing should be the last surface treatment. Shepard pointed out that this is not an option for spoke resonators without large demountable flanges. He reiterated that this is the reason for doing only a light BCP at the end of the cleaning process to maintain as much as possible of the surface quality.
The next question was, if EP is really needed for the field levels, where spokes are used. While Shepard agreed that operation in the field-emission dominated part of the Q-E curve is not an a problem, he believes that electro-

polishing helps with the low-field Q-slope seen in measurements.
The final point of the discussion was related to the surface smoothness as a function of the speed of the electropolish. Kelly reported that faster polishing gives smoother surfaces, which again is a surprising result that needs more investigation.

Processing of the First French Spoke Cavity

S. Bousson, Institut de Physique Nucleaire

Spoke cavities are intensively studied for the low energy part of a high power proton accelerator in the framework of the XADS or EURISOL projects. The fabrication of the first prototype designed by the IPN laboratory is now achieved by the CERCA company. As every superconducting cavity, the processing is an important issue in order to achieve good performances. In this paper, we report on the cavity preparation planned for the spoke prototype: standard chemical treatment and high pressure rinsing (with a modified apparatus).

PROCESSING OF THE FIRST FRENCH SPOKE CAVITY

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CAVITY PROCESSING

Well-known rule:
Cavity preparation is a key issue in order to achieve good performances !!!

The following procedure will be followed for the spoke cavity:

Chemical cleaning
Immediately followed by ultra-pure water **rinsing**
High Pressure Rinsing in class 100 clean room
Assembly (pumping port closed with a cold valve)
Pumping and **leak checking** (still in the class 100 clean room)

Careful transportation from Saclay to Orsay

Mounting on the insert **in front of a laminar flow**
Pumping and then **opening** of the valve

BCP CHEMICAL ETCHING

υ First tests: Cavity plunged into the acid bath

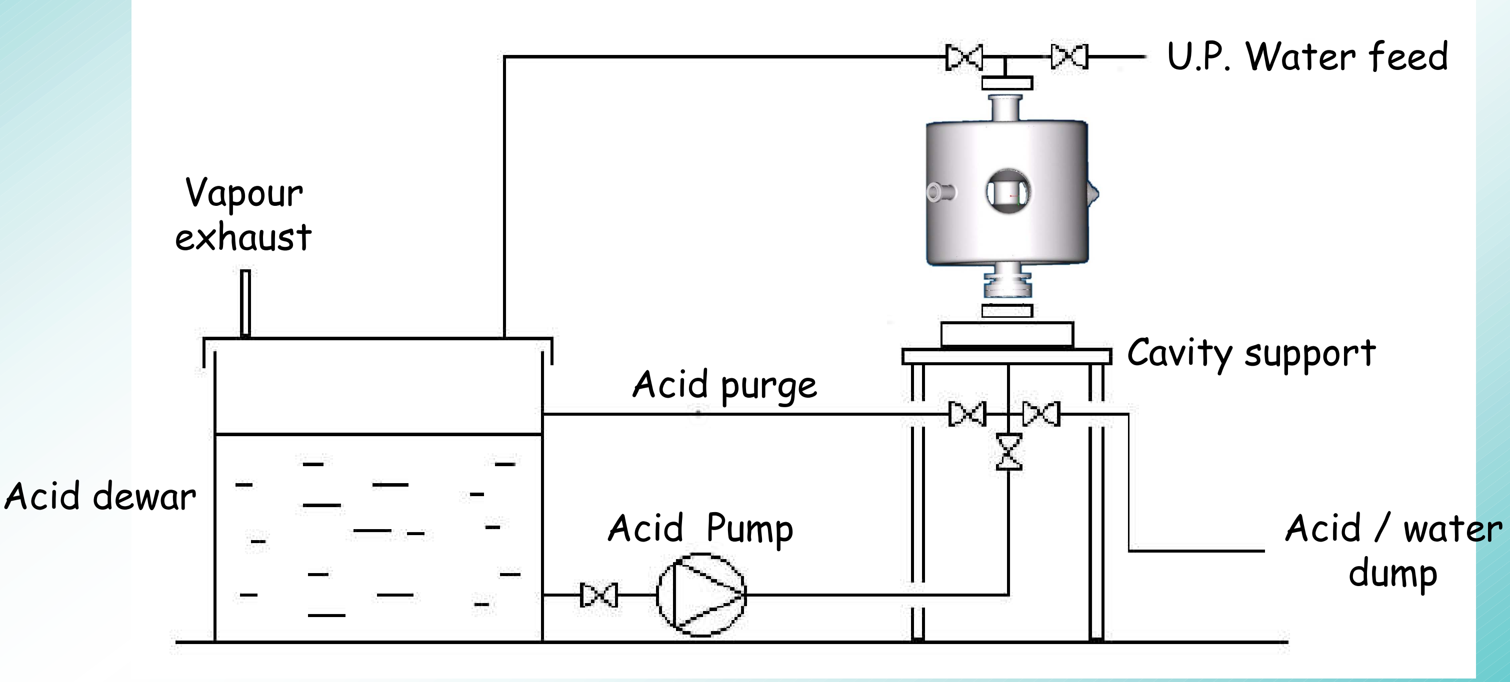
Mixture of HF : HNO_3 : H_3PO_4 in the volumetric ratio of 1:1:2

150 μm removal for the first chemistry

ϖ In the near future: integrated chemical etching

Circulation of the acid in the cavity using a pump

Immediate rinsing with ultra-pure water

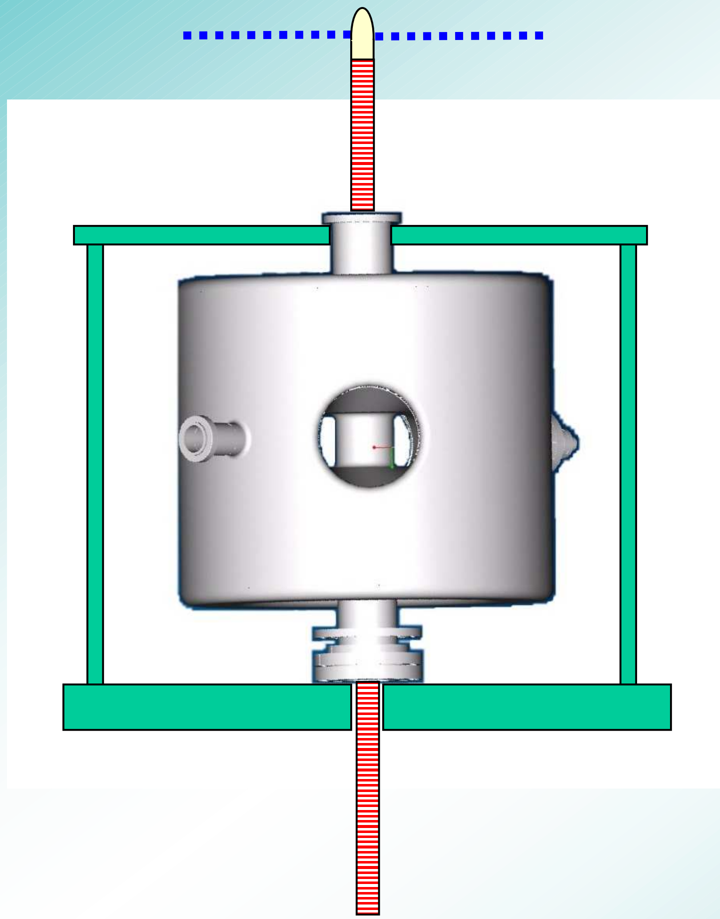


CHEMISTRY: OPEN QUESTION

Any idea of the hydrodynamic of the acid in the spoke cavity during integrated chemistry ?

Are every part of the cavity etched the same way ?

HIG PRESSURE RINSING

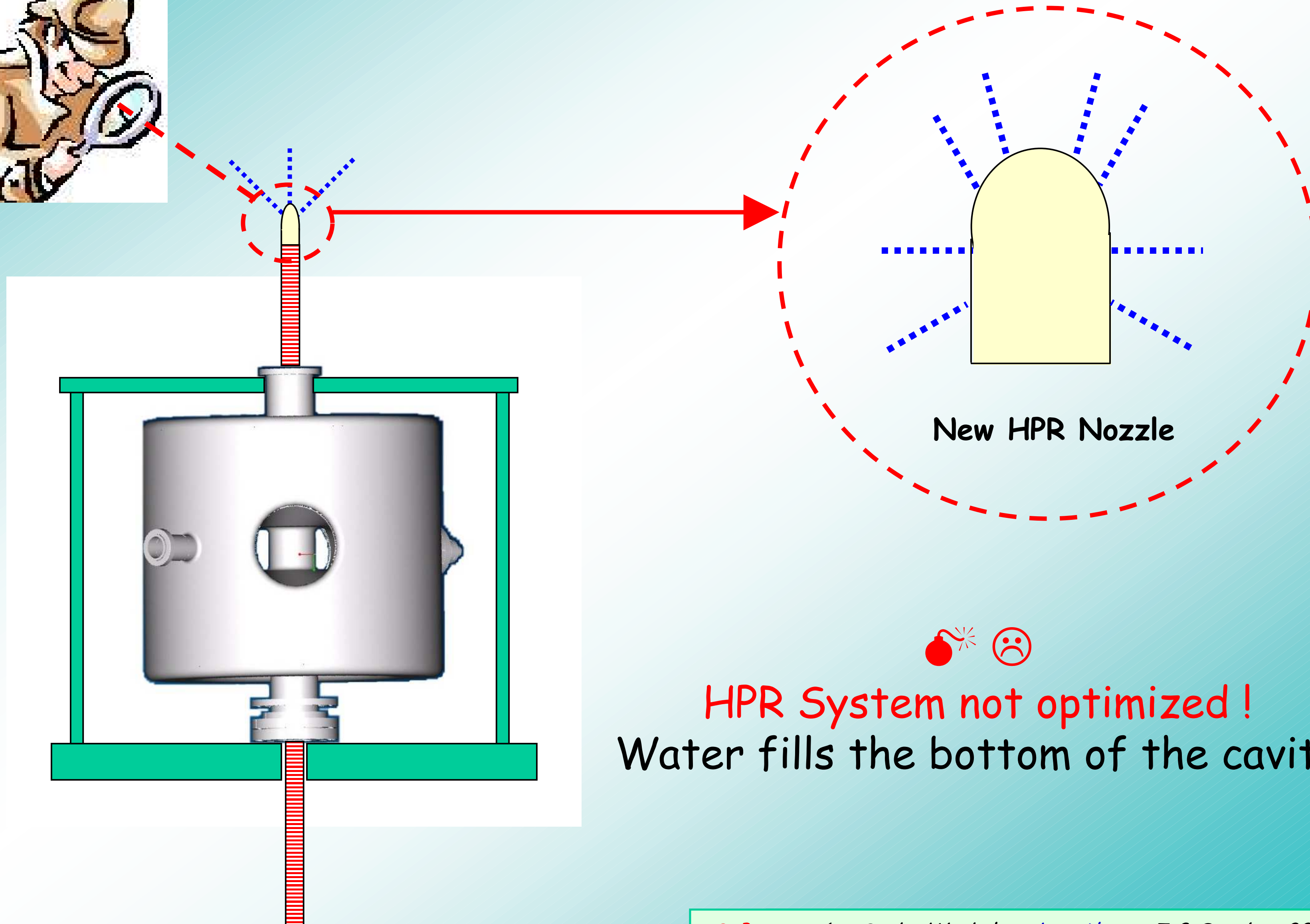


The CEA Saclay HPR:
- 80 Bars
-The cavity is fixed on a rotating support (about 2 turns/second)
- Nozzle: 3 horizontal jets

The CEA Saclay HPR apparatus will be modified to be adapted at the spoke shape.

The HPR nozzle will be changed

THE MODIFIED HIGH PRESSURE RINSING APPARATUS

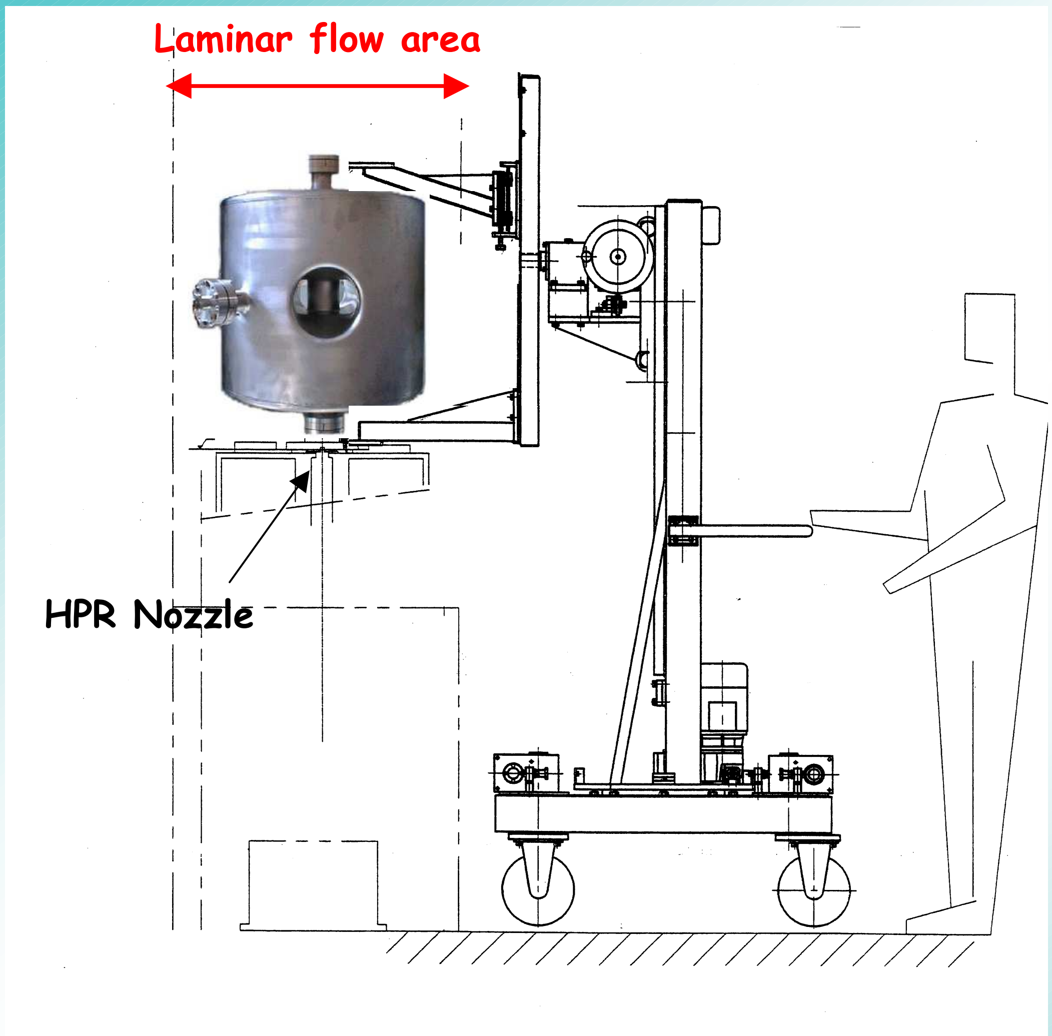


💣 ☹

HPR System not optimized !

Water fills the bottom of the cavity

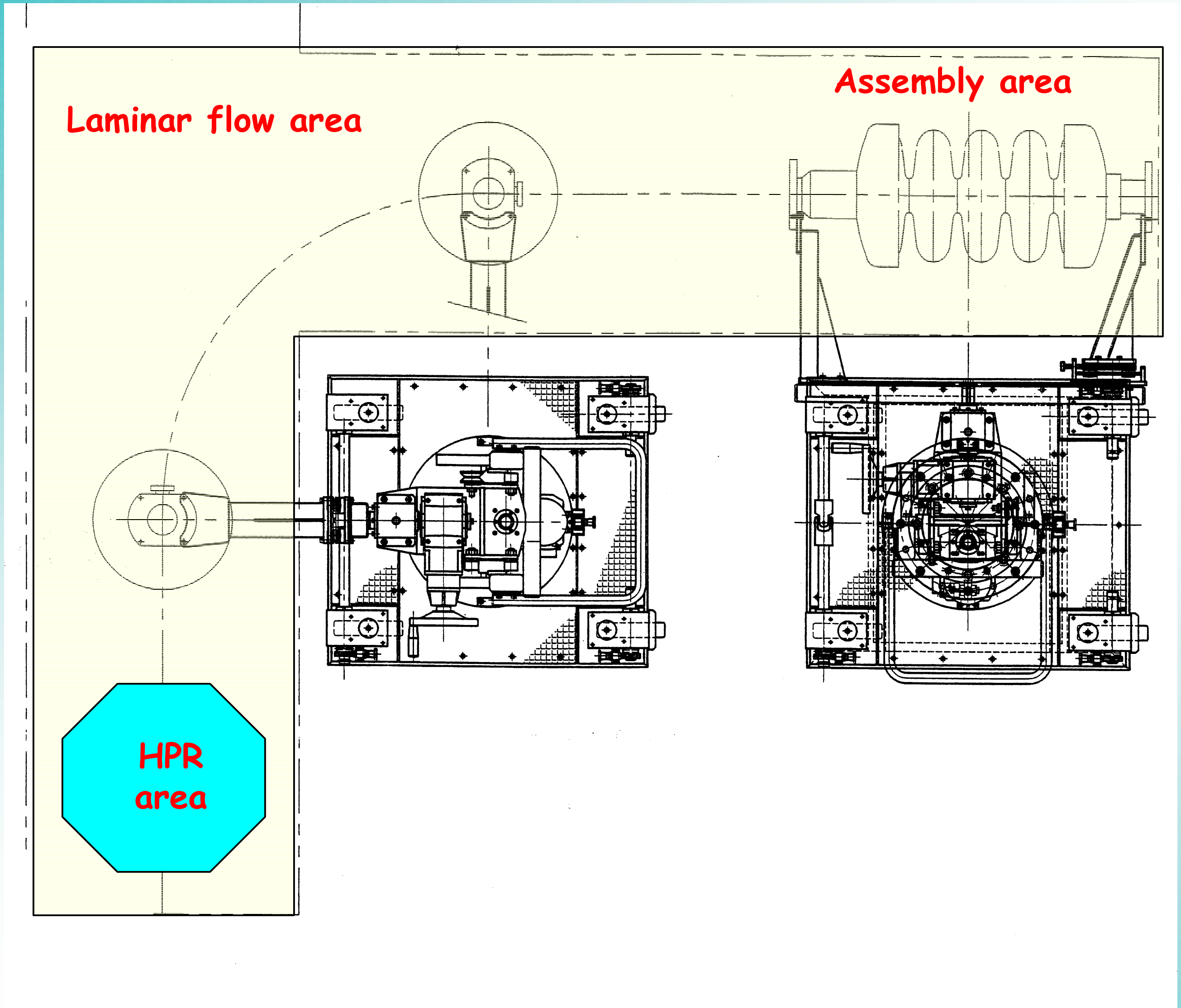
THE HANDLING SYSTEM (1)



Special care has been taken for the handling of heavy cavities (Spoke, Multi-Cell...)

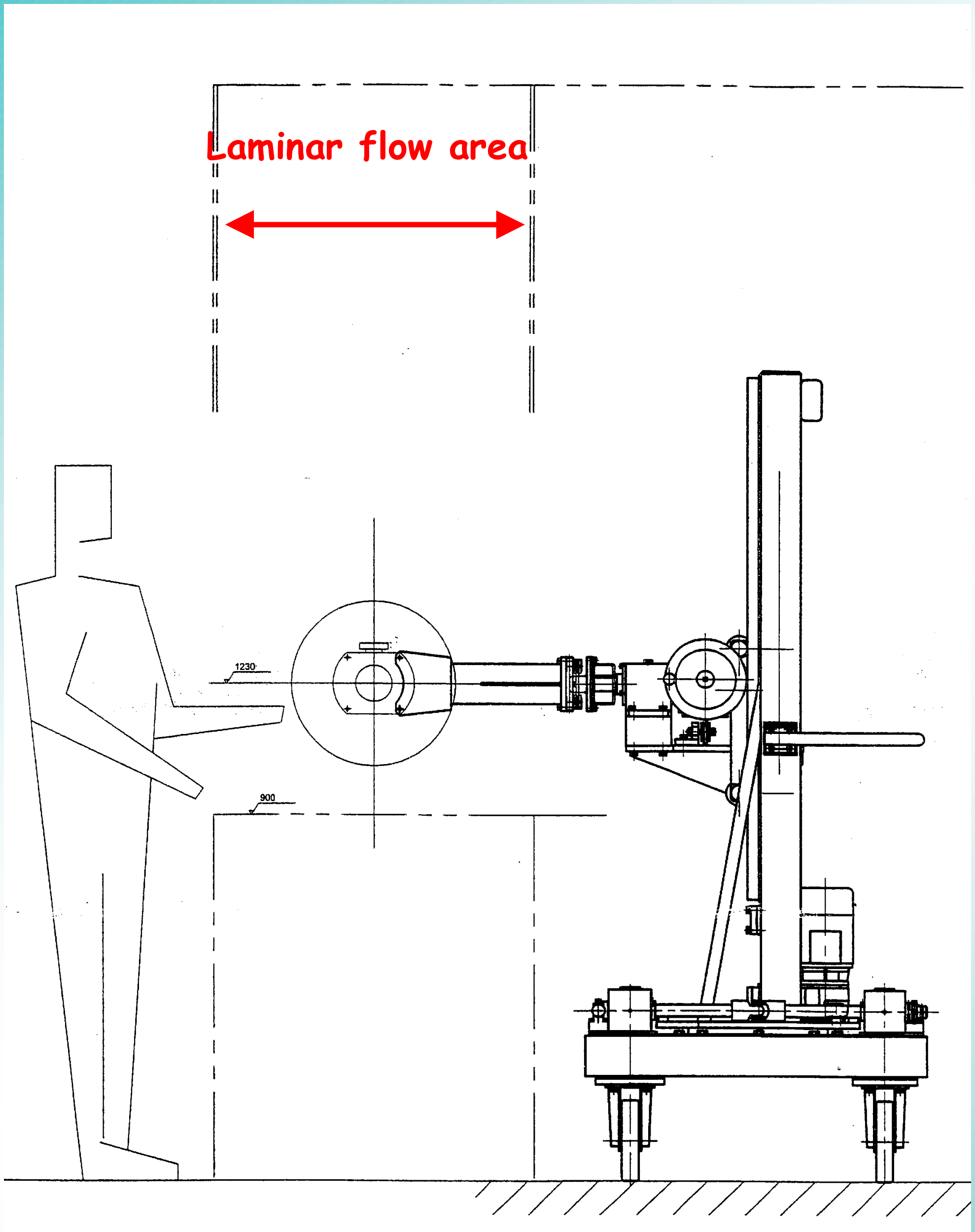
A dedicated trolley was studied and fabricated to easily handle cavities (of different geometry) in the clean room.

THE HANDLING SYSTEM (2)



Cavity movement in the clean room from the HPR area to the assembly area.

THE HANDLING SYSTEM (3)



The cavity is hold by the trailer in the assembly area

FUTURE AND QUESTIONS

Cavity preparation

In-situ baking (reducing the Qo slope)
Helium processing
Cavity heat treatment at 800°C (Qo disease) ?

Cavity testing:

What diagnostic needed ? T-map, X-rays...

Discussion on "Processing of the First French Spoke Cavity" by Sebastien Bousson

The discussion started with BCP issues. It was pointed out that etching rates are very dependent on flow and temperature and that special efforts have to be made to achieve homogeneous etching rates in spoke resonators. Delayen and Krawczyk pointed out that Jlab had experienced a factor of two difference in etch-rate already for elliptical cavities. A flow-diverter helped to improve the situation. Shepard and Kelly added that they needed a recirculating system through all spoke cavity ports to suppress bubble creation and improve homogeneity. One might even have to consider rotating a cavity. The sketch of the BCP system to be used in Orsay has a cavity orientation that has the beam pipes on top and bottom of the stand. In this orientation gas would be trapped in the top part of the end cap. Orsay will reconsider the BCP setup.

Next the HPR system was addressed. Orsay uses an electropolished stainless steel nozzle. While Jlab for this type of nozzle experiences corrosion, LANL checked this type of nozzle by dissection and did not find any corrosion, even after years of use of one of their nozzles. Shepard noted that this might be an effect of the actual water pressure and the size of the holes. Again, the sketch of the HPR system shown meant stagnant flow for the water. Bousson acknowledged that this needs to be addressed. While their first setup will have to be done in this orientation, a future redesign is worked on.

Details of the cavity treatment were clarified next: The water is not cleaned with ethanol after the HPR, it is not dried with nitrogen gas, but only in laminar air-flow in the cleanroom. For the future they are thinking about in-situ baking to reduce the Q-slope of these structures. This latter approach was questioned, as it does not address the low field slope, but the less important high-field slope. Tests at ANL did show little effect of this baking.

Further comments on heat-treatment warned of undesired effects: in-situ baking will improve the BCS resistance, but it might increase the residual resistance with a negative net result. Also, SNS for a 800 degree Celsius heat treatment experienced too soft cavities (with material from two different vendors). They needed to reduce the temperature to 600 degrees Celsius. Orsay is thinking of using 650 degrees Celsius.

Finally the quenches of the LANL cavity were discussed. Tajima estimated that around 100 W were put into the cavity at the quench level. This indicates that these quenches are not due to a microscopic defect, but due to electron bombardment from field emission. This can result in local thermal instability and film boiling.

Preparation procedures for testing the LANL/AAA spoke cavities

T. Tajima, LANL

The procedures consist of (1) buffered chemical polishing (BCP), (2) rinsing and high-pressure rinsing at 1000 - 1200 psi with ultra-pure water and installation of flanges, couplers and a vacuum valve in a class <100 clean room, (3) set up on the cryostat insert, leak test and baking at ~ 110 ºC for about 2 days, (4) putting the insert into the vertical cryostat and pre-cool it indirectly by filling a vacuum-isolated layer between inner and outer vessels of the cryostat with liquid nitrogen, which leads to a cavity temperature ~ 250 K over night, and (5) fill the cryostat with liquid helium. These procedures will be described in detail.

Preparation Procedures for Testing the LANL/AAA Spoke Cavities

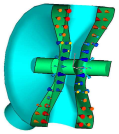
Tsuyoshi Tajima

LANL

Workshop on the Advanced Design of Spoke Resonators

Los Alamos, NM, USA

October 7 and 8, 2002

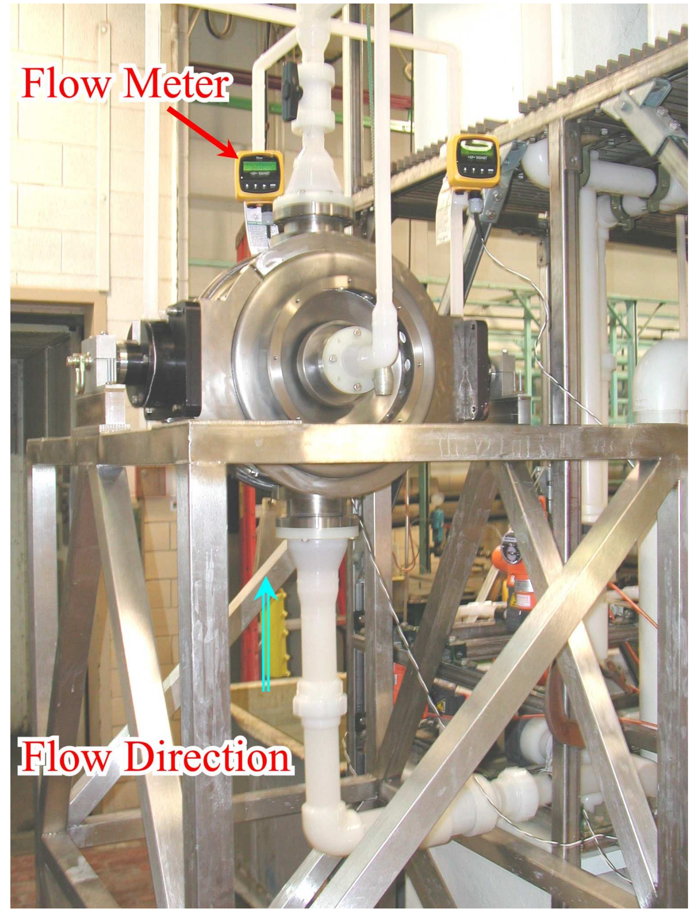


Buffered Chemical Polishing (BCP)

$HF:HNO_3:H_3PO_4=1:1:2$ by volume at < 15 ºC

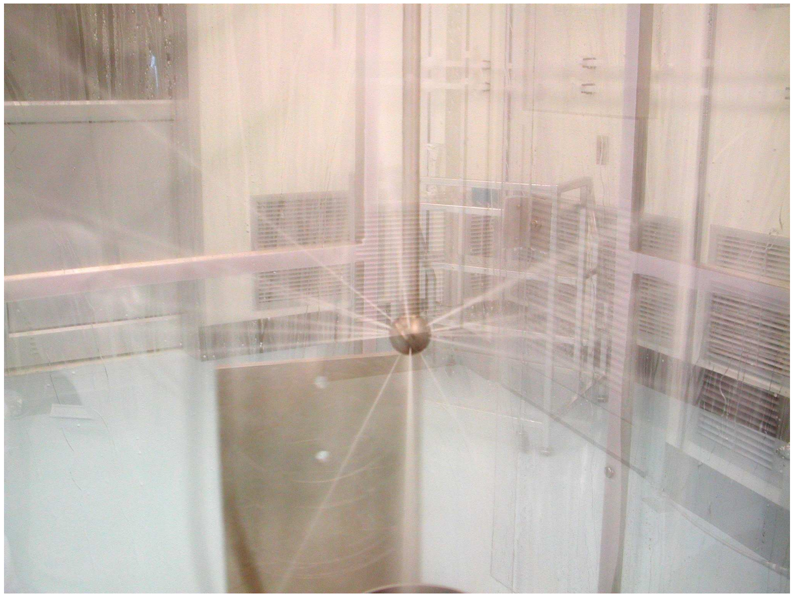
EZ02

EZ01



High Pressure Rinsing (HPR)

- Ultra-pure water
- Pressure 1000-1200 psi (69 – 83 bar), ~10 L/min.
- At 4 positions
  - beam port 1 (10 min.)
  - radial port 1 (10 min.)
  - beam port 2 (10 min.)
  - radial port 2 (20 min.)
- Sweep speed
  - Up ~ 4 mm/s
  - Down ~ 7.5 mm/s
- Table rotation ~ 23 rpm



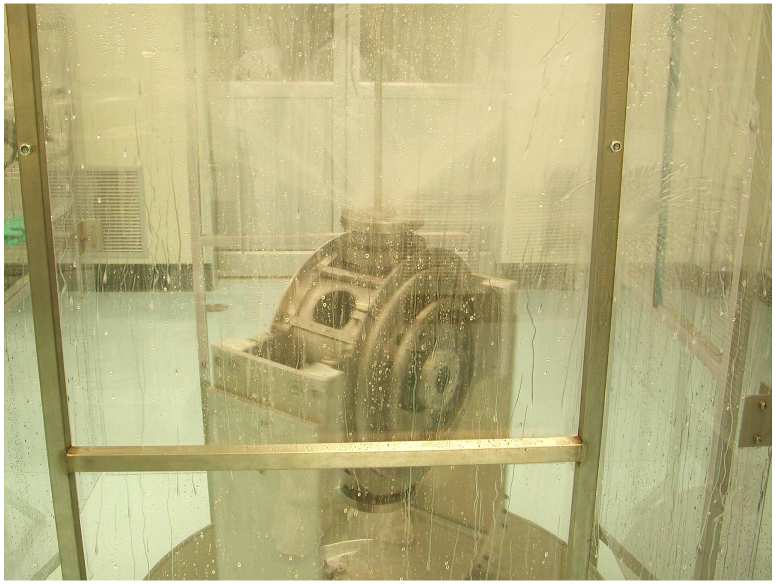
Nozzle

Outer diameter: 31.75 mm

Holes: 457 μm-diam., 3.81 mm long

No. of holes: 21

11 different angles to cover all the surfaces

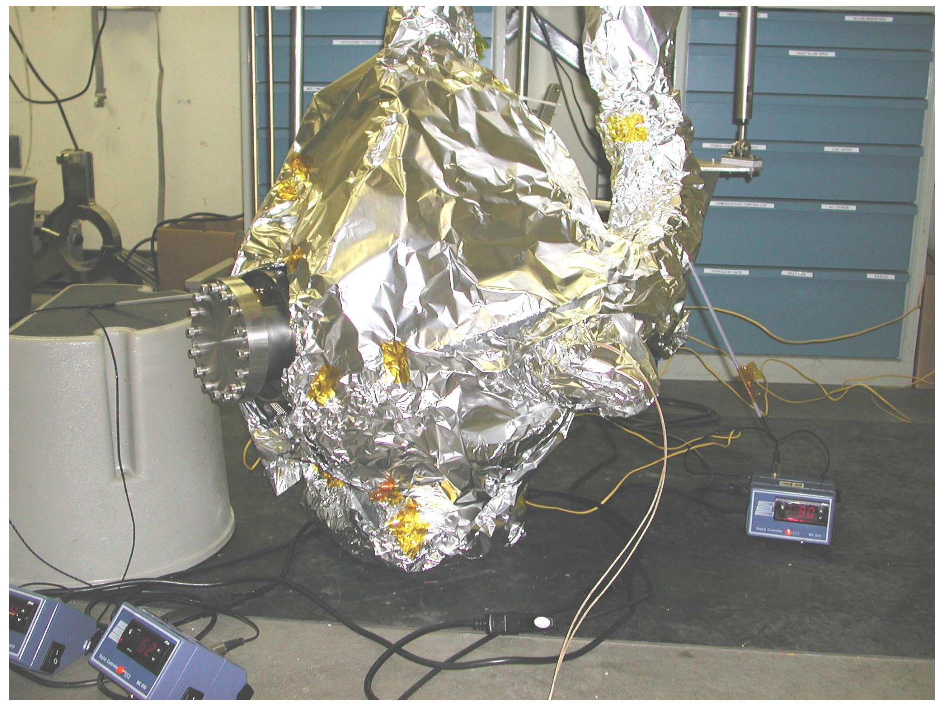


Assembly in the Clean Room

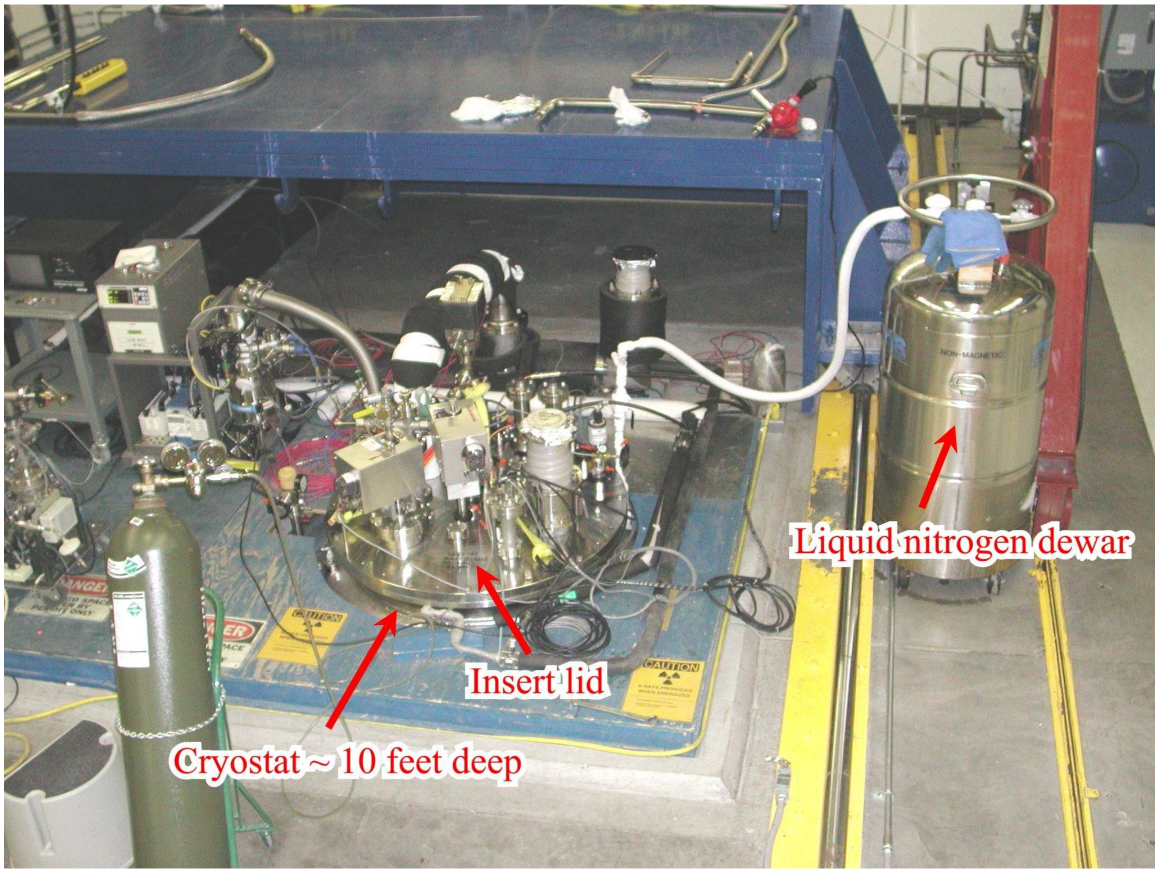
- Clean room class 100
- For tapped holes, anti-seize grease is used
- For through holes, SS bolts and silicon-bronze nuts are used.
- Nominally, all the flanges are Conflat, but indium seals were used to attach Nb blank flanges on the large radial ports for the vertical tests.
- Special polyethylene cover was made to attach indium on the flat surface inside of Conflat knife edge.

Set Up on the Insert and Baking

Baking at ~ 110 ºC for ~ 2 days
Indium < 80 ºC

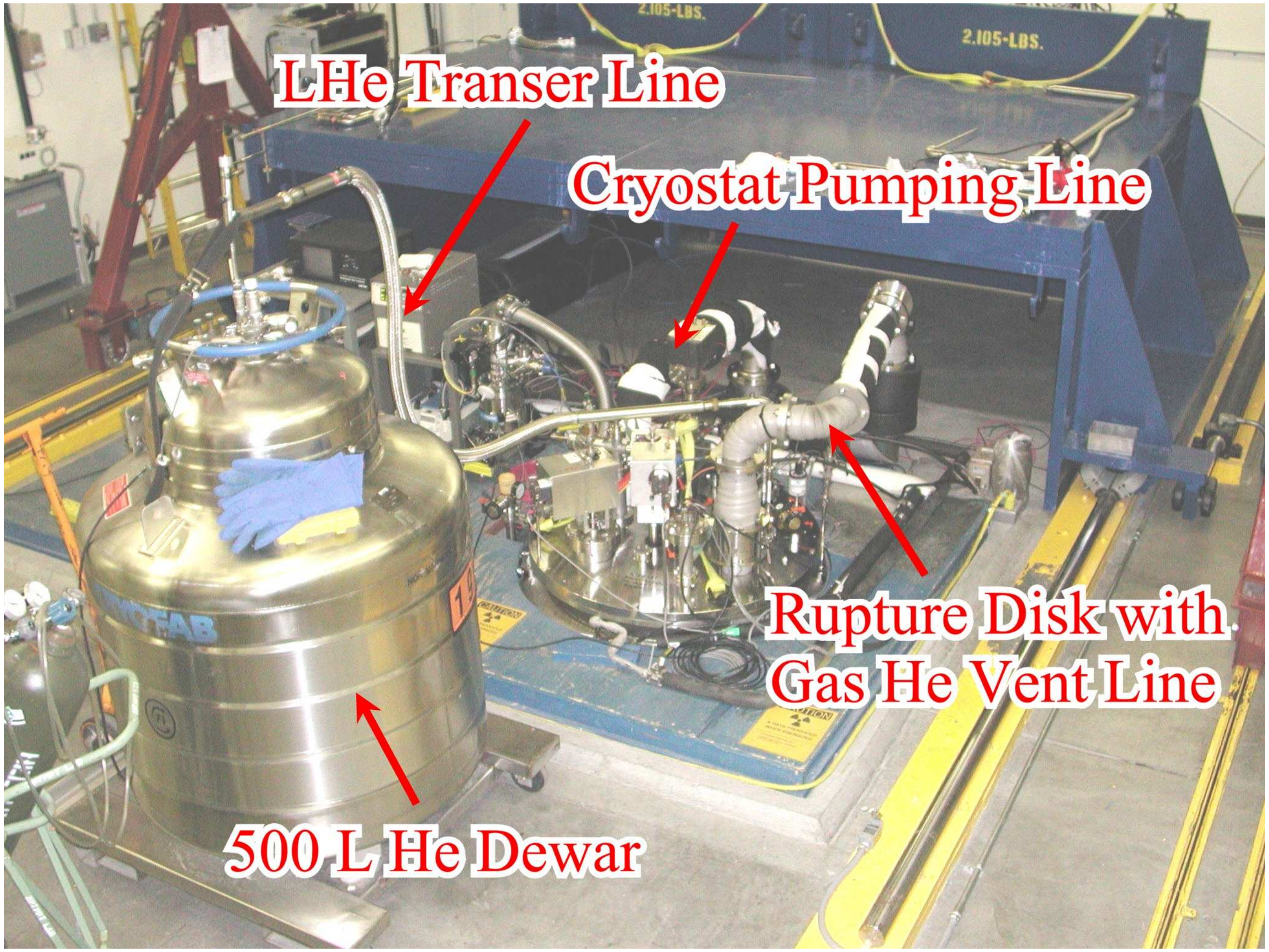


Indirect Pre-Cooling with LN



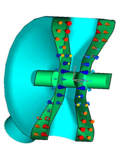
- Fill the vacuum-insulated layer between inner and outer vessel with LN
- This operation is carried out one day before LHe transfer
- When LHe transfer starts, the cavity temperature is ~ 250 K

Helium Transfer and Testing



RF Tests and Helium Processing

- LavView6.1 software has been used for automated data acquisition. Web broadcasting or monitoring of background data has been very useful.
- Helium injection to the cavity has been automated so that we can control the amount of injection, but it has been unable to control the amount precisely yet.



Summary and Issues for Improvement

- BCP, HPR, clean assembly, setting on the insert, baking and testing at 4 K and 2 K were described.
- Issues we are planning to improve in the future
  - Better BCP flow control and may try EP in the future
  - Face shield during assembly to avoid contamination with particles from human face
  - Better anti-seize coating for bolts
  - Better control of He injection during helium processing

Discussion on "Preparation Procedures for Testing the LANL/AAA Spoke Cavities" by Tsuyoshi Tajima

For the LANL processing talk only one suggestion came up: LANL is using stainless steel bolts for tapped holes. This requires to work with anti-seize in the cleanroom, an undesirable situation. It was suggested to use silicone-bronze bolts instead, which would remove the requirement of working with anti-seize. LANL will change its procedures accordingly.

Test Results

Tsuyoshi Tajima: "*Test Results of the LANL/AAA Spoke Cavities*" (Abstract | Viewgraphs | Discussion)

Mike Kelly: "*ANL/RIA*" (Testing and processing were covered jointly in the processing session)

Test results of LANL/AAA spoke cavities

T. Tajima, LANL

Test results of the LANL/AAA 350-MHz 2-gap spoke cavities EZ01 and EZ02 will be presented. They were fabricated by Zanon, Italy. The cavity EZ02 has shown a maximum accelerating field of 12.9 MV/m after helium processing. The limitation was field emission and associated quench. The initial low-field Q_0 with two large side ports blanked with niobium flanges was 1.04E9, but it degraded by 48 % when one of the niobium blank flanges was replaced with a stainless steel (SS) bellows. This degradation was significantly larger than we predicted (4 - 5 %) with MAFIA and MWS calculations. We therefore will test this again to confirm that this degradation is attributed to the SS bellows.
We also tested Q disease with the cavity EZ02. Q disease occurred after holding the cavity at 100 - 132 K for 61 hours, i.e., Q_0 degraded by a factor of 1.8 (0.7 MV/m) to 2.4 (7.1 MV/m). The degradation, however, was recovered after warming up to ~ 185 K. To know the detailed temperature and holding time dependence on the degradation, we will test the cavity more systematically in the future.

Test Results of LANL/AAA β=0.175, 350-MHz, 2-Gap Spoke Cavities

Tsuyoshi Tajima
LANL

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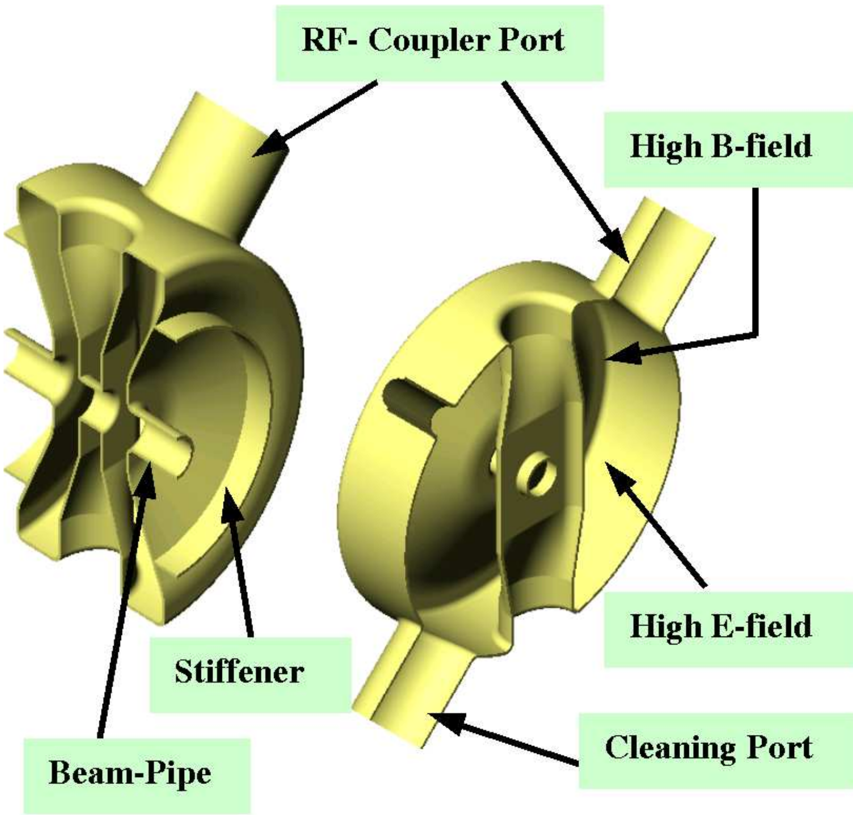
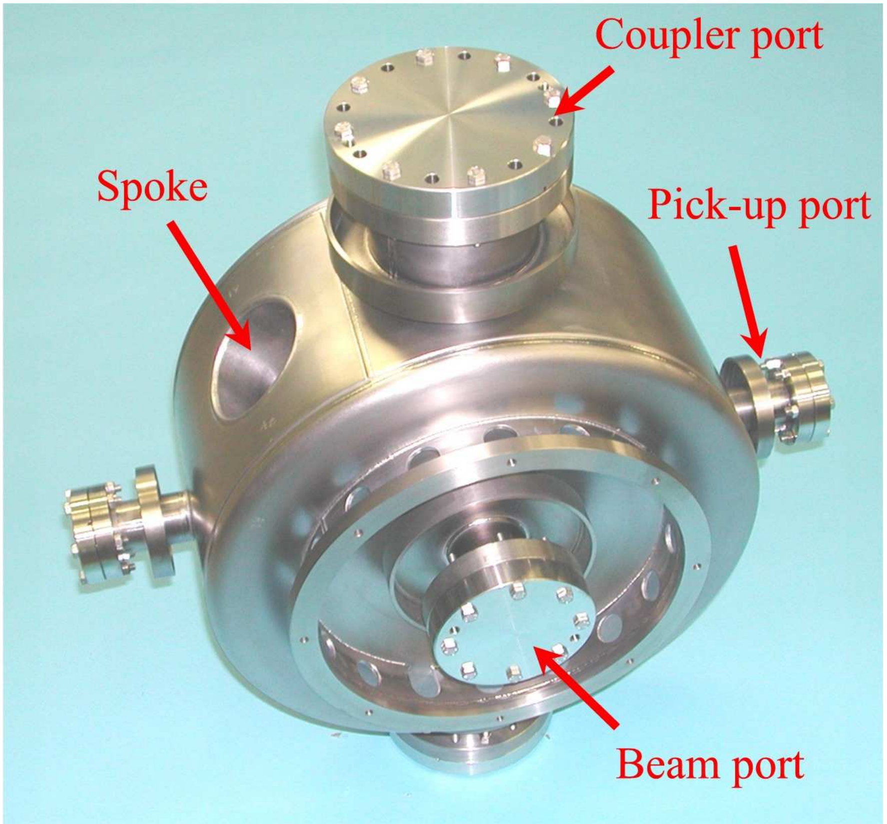
The LANL/AAA Spoke Cavity EZ01 and EZ02





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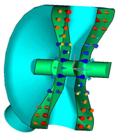
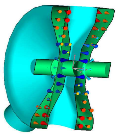
The Cavity Dimensions

Cavity Radius	19.609 cm
Spoke Radius at Base	4.5 cm
Spoke Thickness at Aperture	3.5 cm
Spoke Width at Aperture	11.44 cm
Aperture Diameter	5.00 cm
Cavity Length (gap-to-gap)	9.99 cm
Cavity Overall Length	19.99 cm
Cavity Length (flange-to-flange)	28.6 cm
Coupler Port Diameter	10.3 cm
Pick-up Port Diameter	3.81 cm
Initial Nb thickness	3.5 mm



RF Parameters

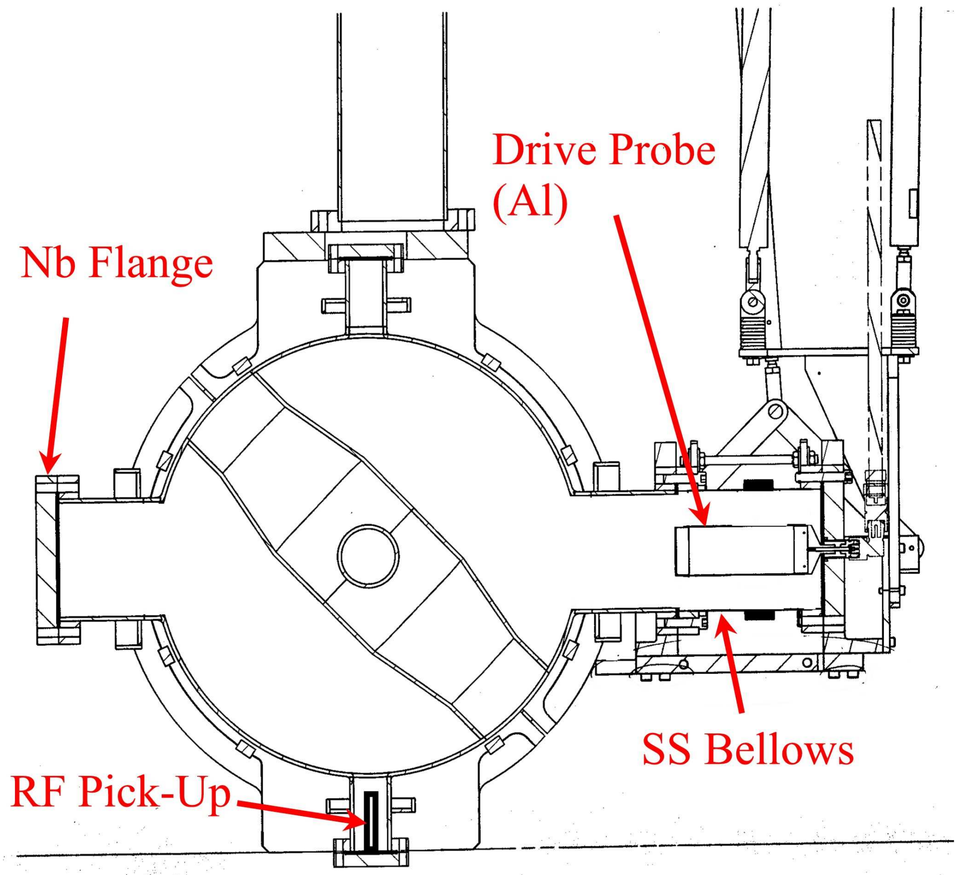
Q_0 (4 K)	1.05E+09 (for 61 nΩ)
T (β_g)	0.7765 (β_g=0.175)
$T_{max}(\beta)$	0.8063 (@ β=0.21)
G	64.1 Ω
E_{pk}/E_{acc}	2.82
B_{pk}/E_{acc}	73.8 G/MV/m
P_{cav} (4 K)	4.63 W @ 7.5 MV/m
R/Q	124 Ω



Test Preparation (Brief explanation)

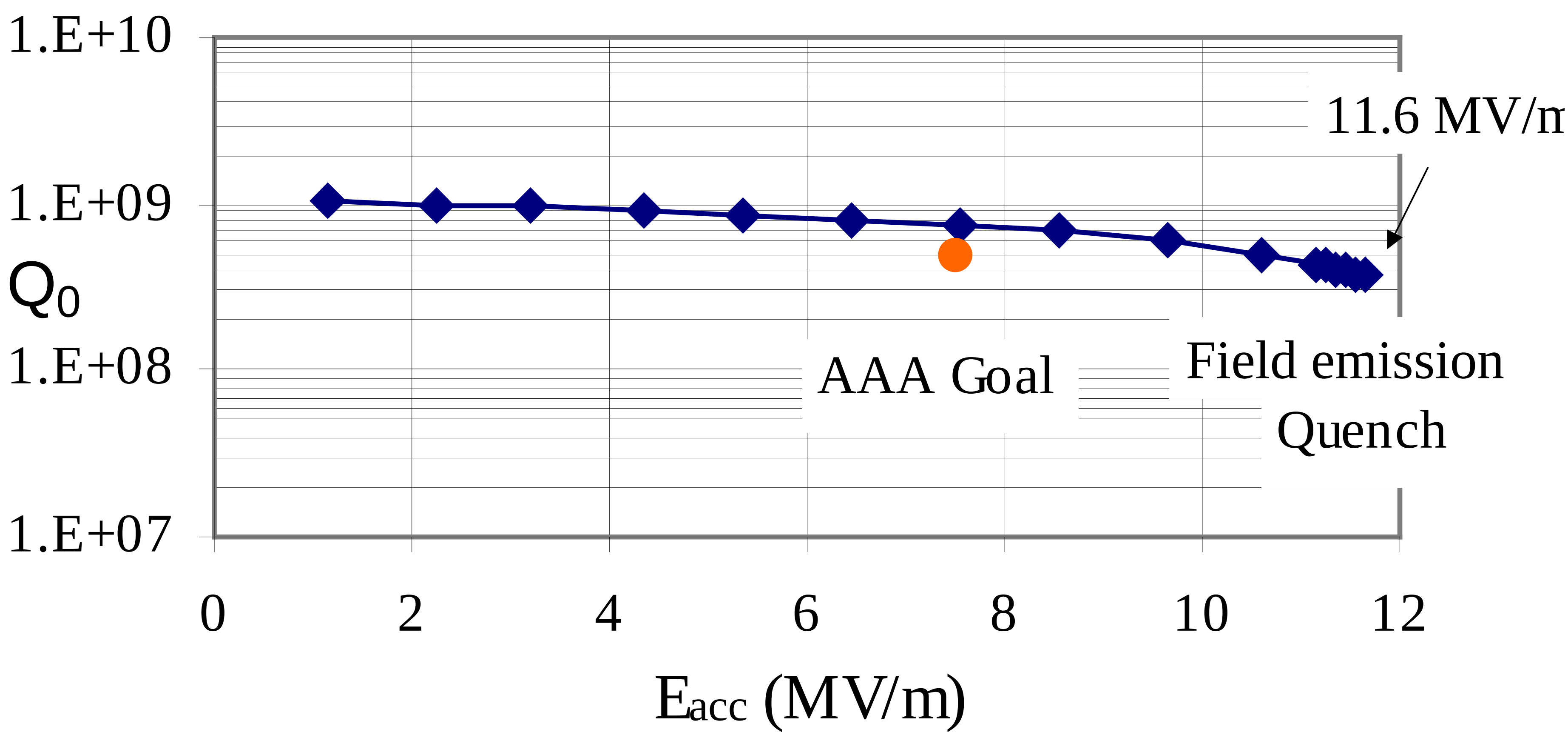
- Buffered Chemical Polishing (BCP) ~ 150 μm with $HF:HNO_3:H_3PO_4$=1:1:2 by volume.
- High Pressure Rinsing (HPR) at 1000 – 1200 psi (69 – 83 bar) for a total of ~50 min.
- Set up on the cryostat insert, pump down and baking at 100 – 110 ºC for ~ 2 days.
- Details will be shown in another talk.

EZ02 – The First Test

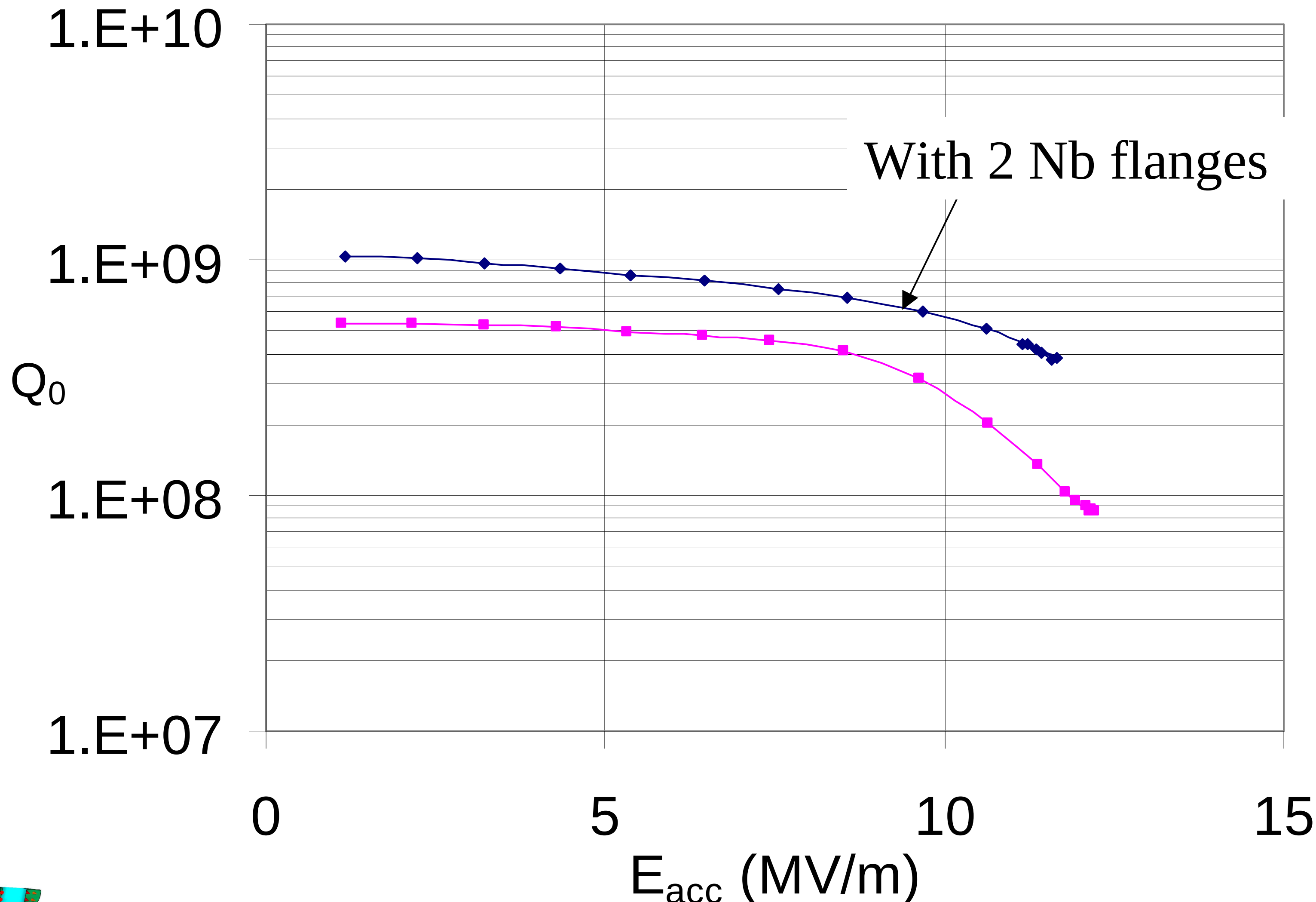


- Tried to couple from the nominal coupler port.
- Loaded Q was 1E6 – 1E7 and could not carry out measurement
- RF loss at SS bellows and Al probe ??

EZ02 with Nb flanges on the arge radial ports – 4 K test

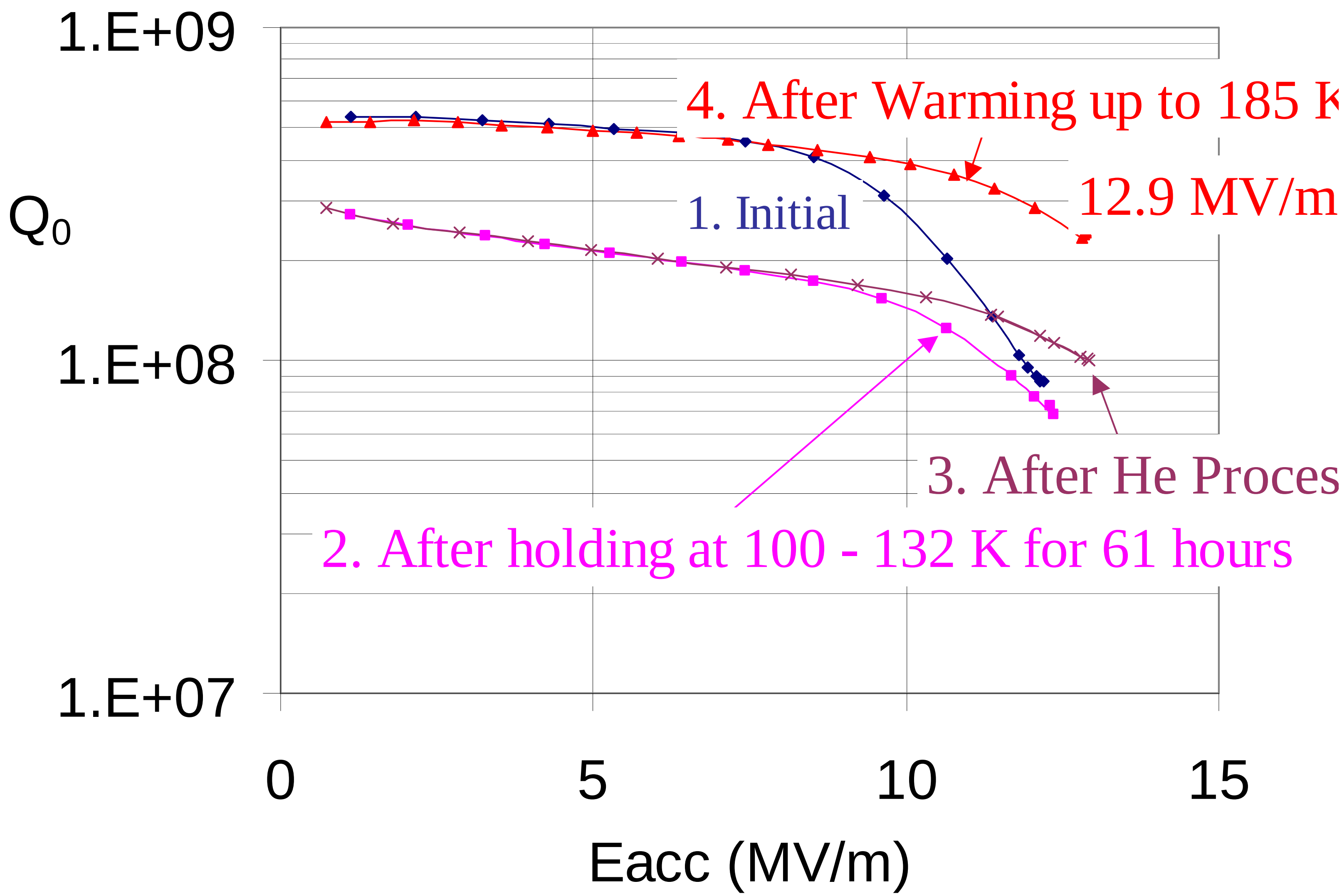


EZ02 with 1 Nb flange and 1 SS bellows on the large radial ports – 4 K



- 48 % decrease of Q_0 at low field.
- Need another test to clarify discrepancy with calculations (4 - 5 %)

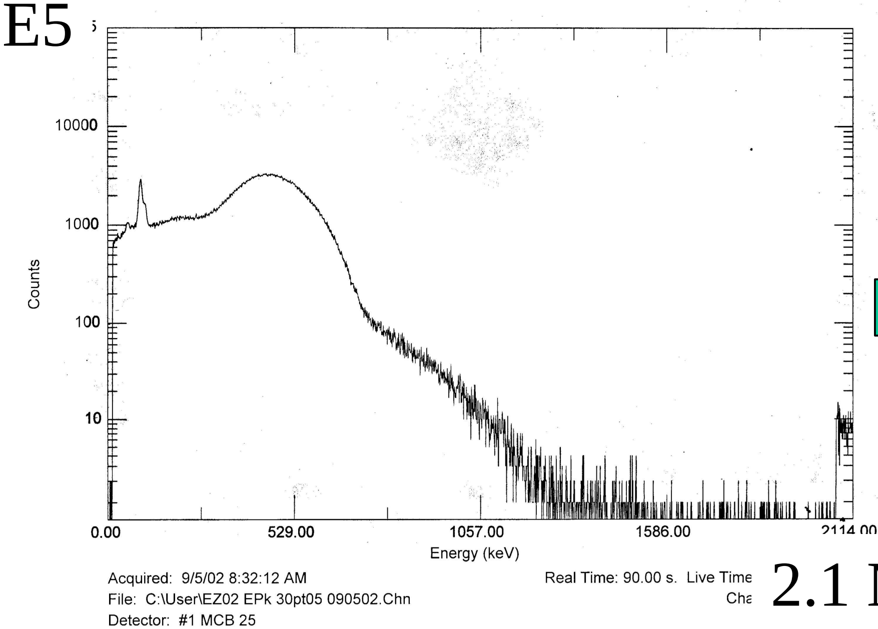
EZ02 Test on Q Disease and He Process



Reduction of X-ray due to He Processing

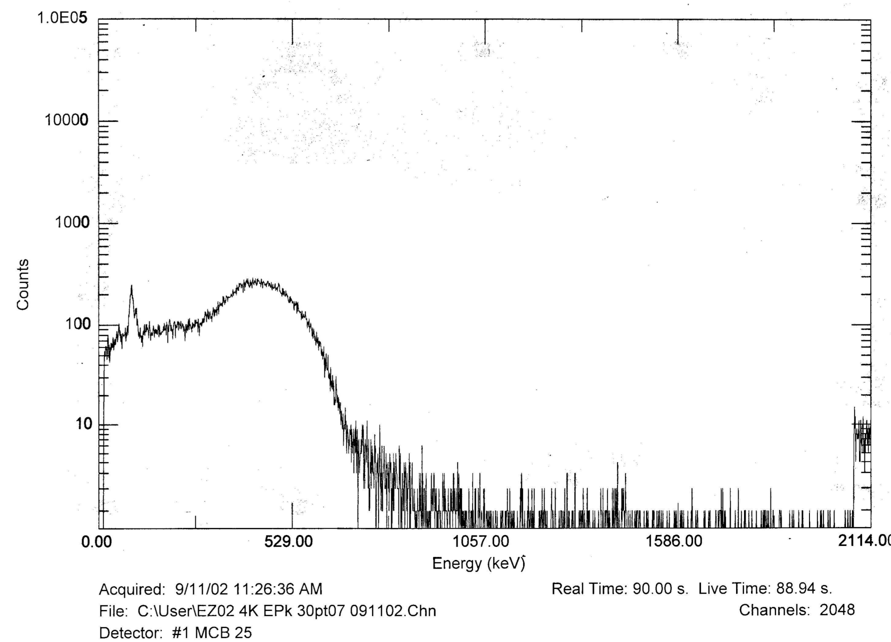
Before

1E5



2.1 MeV

After He Processing

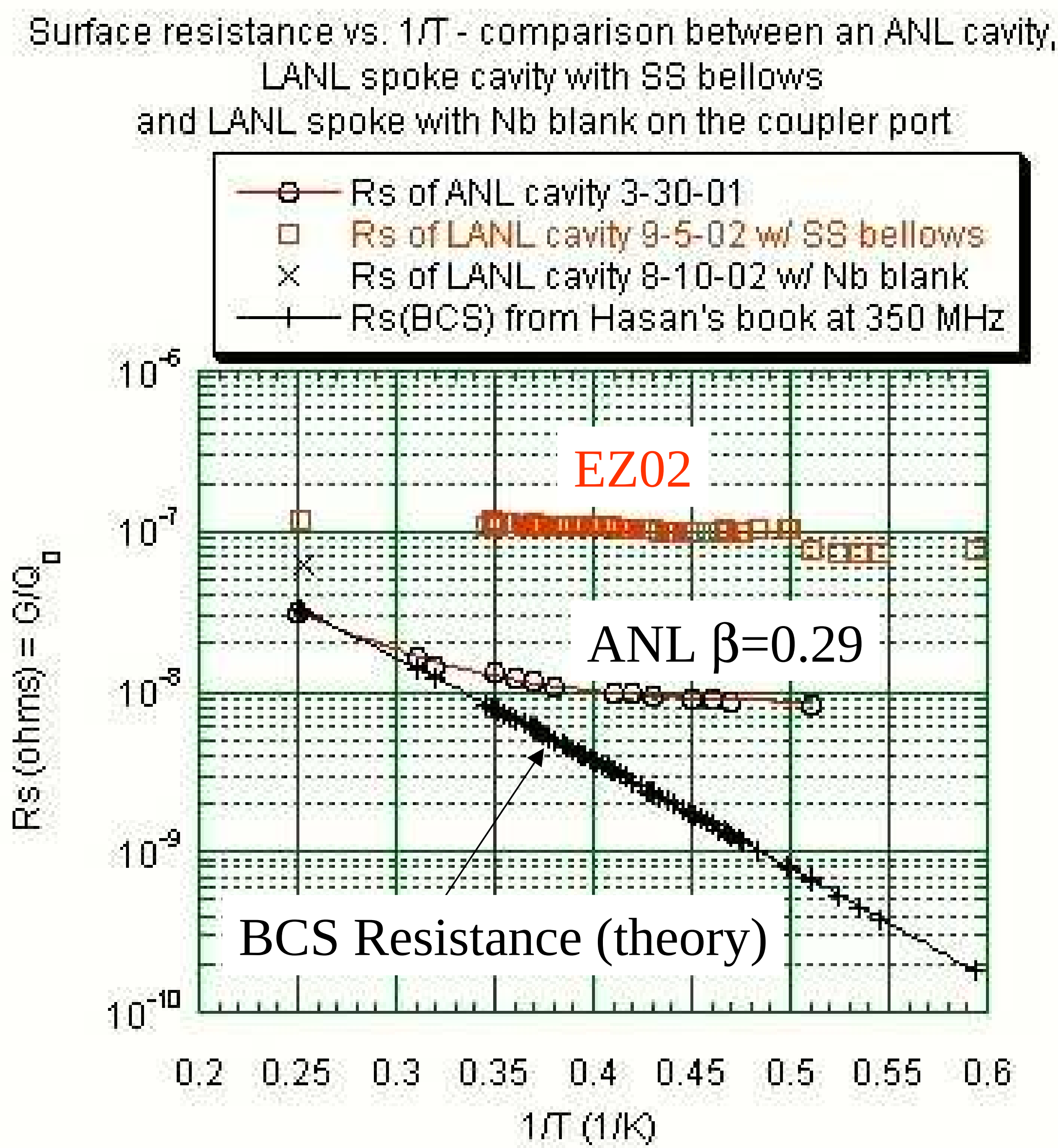


At E_{acc} = 10.6 MV/m

X-ray counts for 90 seconds

EZ02 with SS bellows - Temperature Dependence of Surface Resistance

Rs is insensitive to temperature => suggests normal conducting loss



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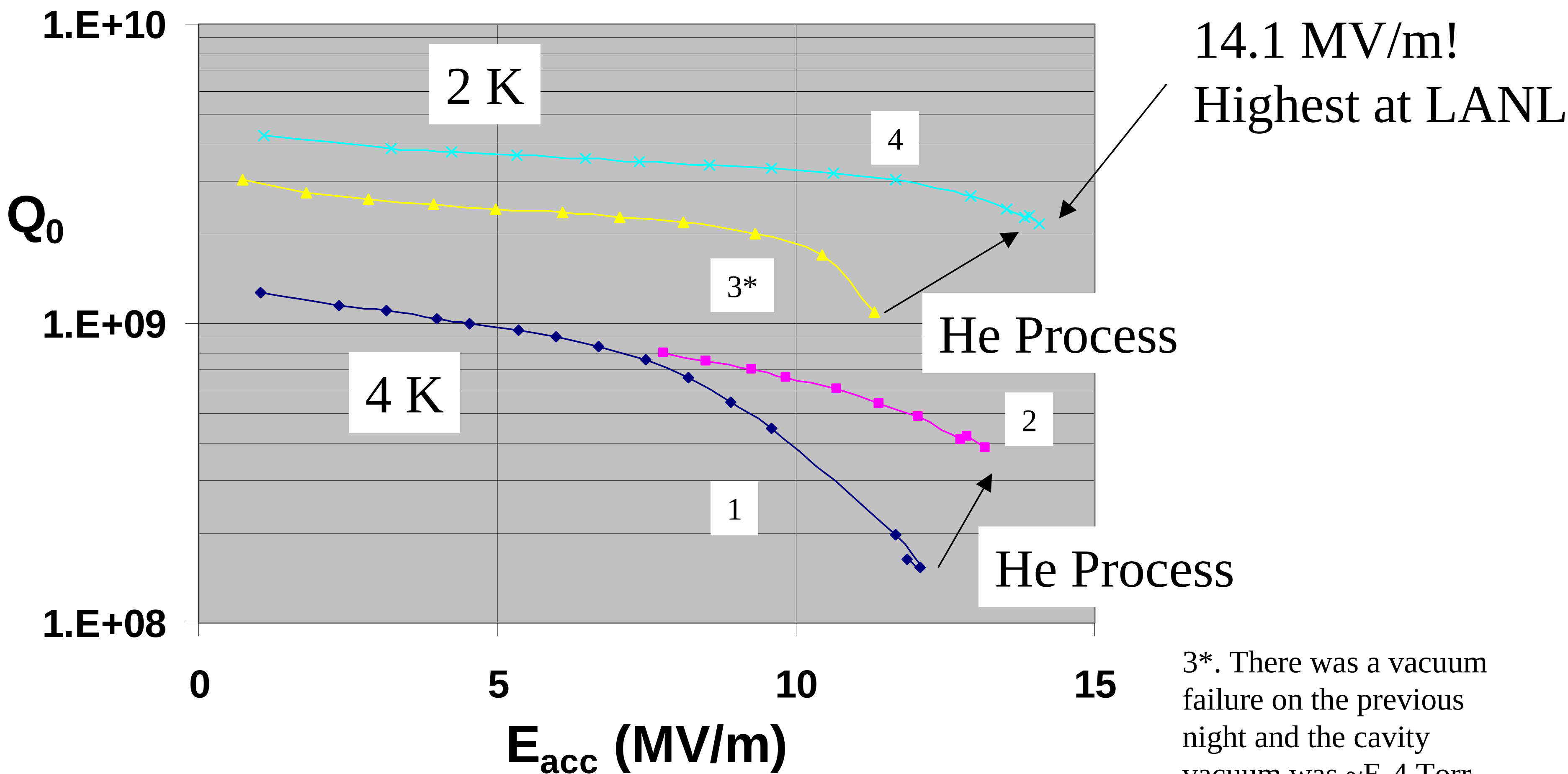
EZ01 First Test with Nb Flanges on the Large Radial Ports



3*. There was a vacuum failure on the previous night and the cavity vacuum was ~E-4 Torr, although it recovered before this test.

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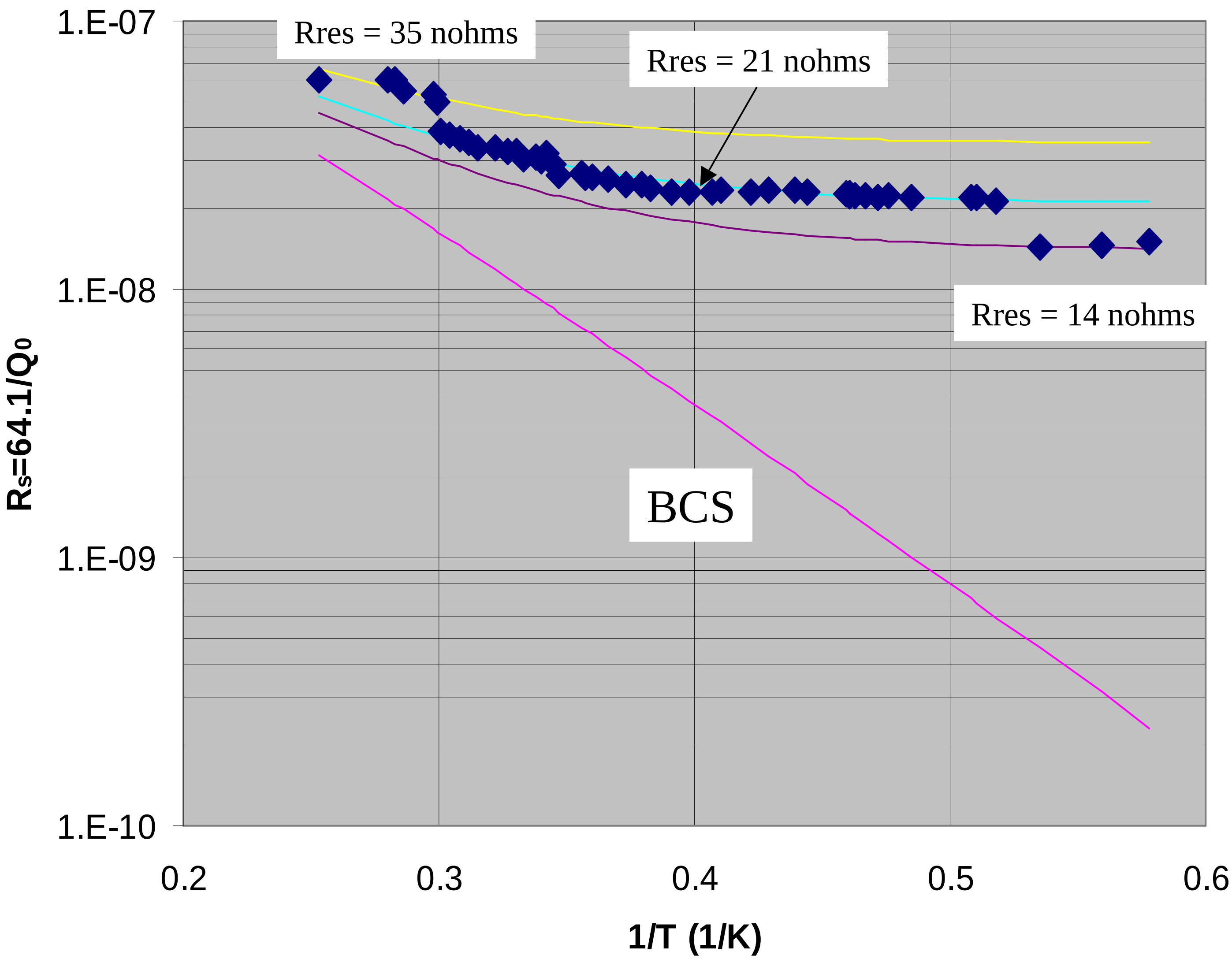
EZ01- Surface Resistance vs. 1/T



Residual resistance was reduced during measurement possibly due to RF processing after vacuum failure (~E-4 Torr).

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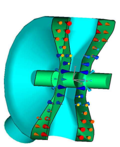
Summary and Future Plans

- The LANL/AAA cavities reached Eacc=12.9 MV/m (EZ02) and 14.3 MV/m (EZ01) as compared to present AAA ADTF design 7.5 MV/m
- Normal-conducting losses at large radial ports need to be studied further.
- The LANL/AAA cavities seem to need more conditioning (MP processing) as compared to ANL-type cavity => This needs to be further studied.
- Q disease occurred on EZ02 after holding at 100 – 132 K for 61 hours, but recovered after warming up to ~ 185 K => More systematic study is planned.



Discussion on "Test Results of LANL/AAA Spoke Cavities" by Tsuyoshi Tajima

The main discussion on the LANL test results was related to the surprisingly high losses in the cavity. Shepard, Delayen and Pagani all saw clear indications of localized losses in the various tested setups that all seem to be related to the large coupler ports attached to the spoke resonator. The predicted losses in the stainless steel outer conductor and the flanges used can not explain these losses. They most likely are coming from the RF-joints, where either the stainless steel outer conductor (with a copper gasket), or the reactor grade niobium flanges (with indium) are attached to the coupler port. A step in the R_s over 1/T curve at 1/T=0.3 coincides with the T_c value for indium. Krawczyk will take a closer look at the RF-joint itself.

Tajima explained that beyond the 100 degree Celsius bake-out, no higher temperature heat treatment is planned.

Tajima had pointed out in his presentation that there was a clear difference in processing time between the ANL and LANL cavities tested at LANL. While the ANL cavities consistently needed less than 30 minutes of processing before the power could be increased to higher levels, the LNAL cavities consistently needed many hours. Shepard answered that this is not a well understood behavior, also at ANL. They experienced processing from 15-20 minutes up to 20 hours for the same type of geometry. There is work in this area that needs to be done.

Introduction 2nd Day

Frank Krawczyk: "*Introduction to the Second Day*"
(Viewgraphs)

Introduction - 2nd Day

Frank Krawczyk
LANL

Workshop on the Advanced Design of Spoke Resonators

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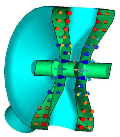
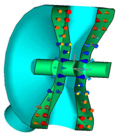


Summary first day

- We saw a wide range of interesting presentations that represent the major issues related to the design of spoke resonators.
- Cleanliness is a key issue for high field operation of these cavities.
- The test results presented show that spoke resonators are capable of gradients well above 10 MV/m, even at very low beta.
- This morning we will talk about control issues, MP, HOMs, power couplers and cryomodules.
- After lunch we will see some ideas related to alternate concepts in structures and operational issues.



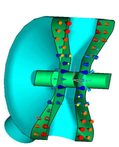
Summary first day

For the discussion session we could talk about:

- Did we see anything that helps simplify resonator design?
- We saw from Ken and Evgeny that short multigap spokes are planned as a next step after testing a variety of single spoke cavities. Are there other important structures/tests that should be done next?
- We saw that spokes at low beta mean poor real estate gradients. Are there any ideas on how to improve that (e.g. low beta multigap spokes, what do these mean to availability?)
- For what applications/parameters are spoke resonators a viable alternative to ellipticals? How high in beta can we go?
- Understanding of the Q-slope to run at 2 or 3 K?

Workshop Program

				2nd DAY		
Time	**Talk**	**Disc.**	**Topic**		**Speaker**	**Chair**
8:30	0:05	0:00	Introduction		F. Krawczyk	
8:35	0:15	0:05	Controls	Overview	J. Delayen	B. Rusnak
8:55	0:15	0:05	Microphonics	RIA Experiments	M. Kelly	
9:15	0:15	0:05	Power Coupler	ANL:RIA	B. Rusnak	T. Tajima
9:35	0:15	0:05		LANL:AAA	F. Krawczyk	
9:55	0:10	0:05	Misc. Issues	Multipacting	F. Krawczyk	B. Rusnak
10:10	0:10	0:05		HOMs for Pulsed Operation	T. Grimm	
10:25	0:00	0:15	Break			
10:40	0:15	0:10	Cryomodule	ANL:RIA	J. Fuerst	C. Pagani
11:05	0:15	0:10		CNRS:XADS/Eurisol	J.-L. Biarrotte	
11:30	0:15	0:10		LANL:AAA	P. Kelley	
11:55	0:00	1:05	Lunch Break			
13:00	0:15	0:05	Alternate Concepts	High β Spokes/Pulsed Ops	K. Shepard	J. Delayen
13:20	0:15	0:05		Consideration of 2K Ops	T. Tajima	
13:40	0:15	0:05		Re-entrant Cavities	A. Facco	
14:00	0:15	0:05		SC CH Cavities	A. Sauer	
14:20	0:10	0:05		RF-Focussing Spoke	B. Garnett	
14:35	0:00	0:30	Discussion	What do we need to advance the technology?	All	K. Shepard
15:05	0:00	0:10	Closing Remarks		F. Krawczyk	
15:15			END			
Talks	**7:45**					
Disc.	**5:10**					



Controls/Microphonics

Jean Delayen: "*Controls - Overview*"
(Abstract | Viewgraphs | Discussion)

Mike Kelly: "*Microphonics Measurements in Spoke Cavities*"
(Abstract | Viewgraphs | Discussion)

Controls - Overview
J. Delayen, Jefferson Laboratory

Except in the case of extremely high beam loading, the frequency of superconducting cavities tends to vary, during operation, by amounts comparable to their bandwidths. The various sources of frequency variations are reviewed as well as means to compensate and control them.

CONTROLS
--
OVERVIEW

Jean Delayen

Jefferson Lab

Spoke Resonator Workshop

Los Alamos

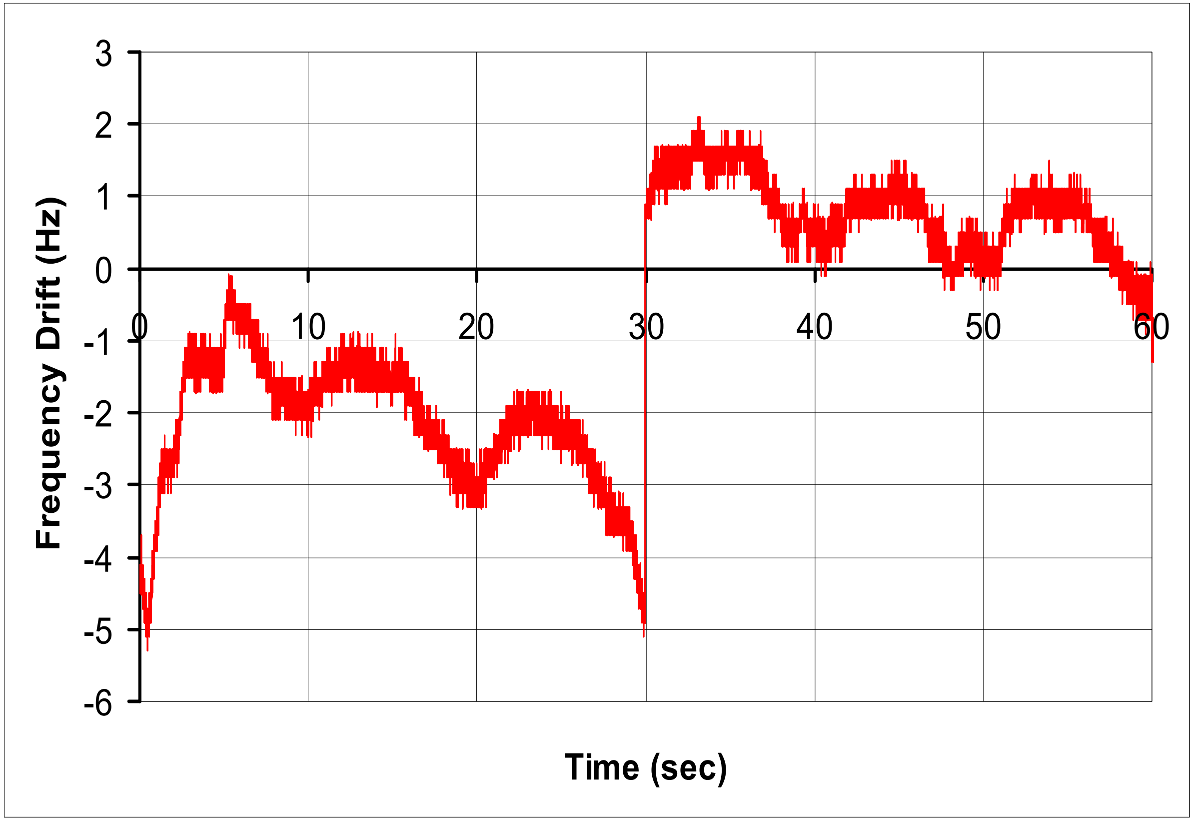
7-8 October 2002

Sources of Frequency Variations

- Slow Environmental Sources, Drifts
  - thermal effects, cryogen pressure
- Fast Environmental Sources, Dynamical Effects
  - ambient vibrations, microphonics
- Coupling between Electromagnetic and Mechanical Modes through Radiation Pressure
  - ponderomotive effects, Lorentz detuning
- Frequency Tuners
  - mechanical, piezo

Slow Frequency Drifts

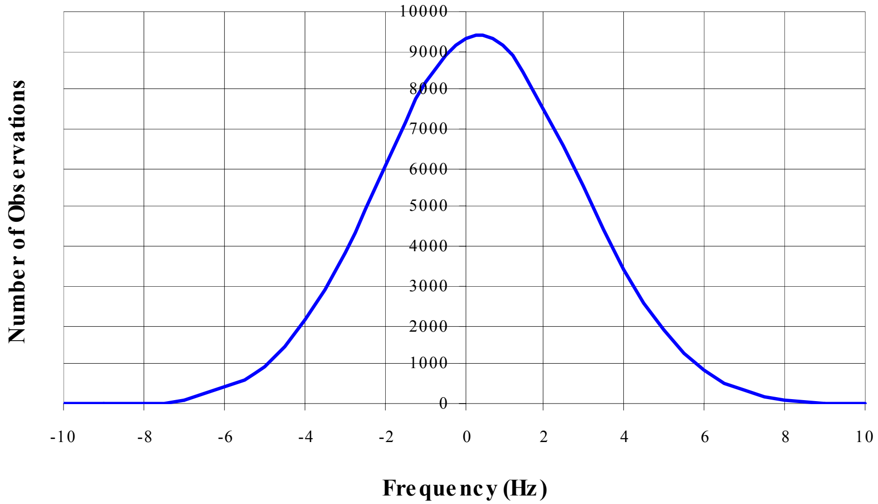
Measured sensitivity : 95 Hz/torr

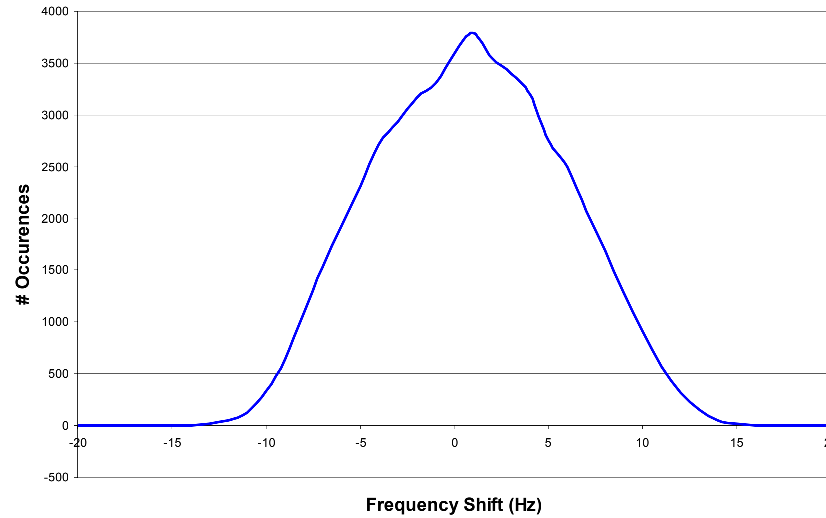


Cavity #2

Microphonics (probability density)

6-cell 805 MHz, β=0.61 in cryomodule





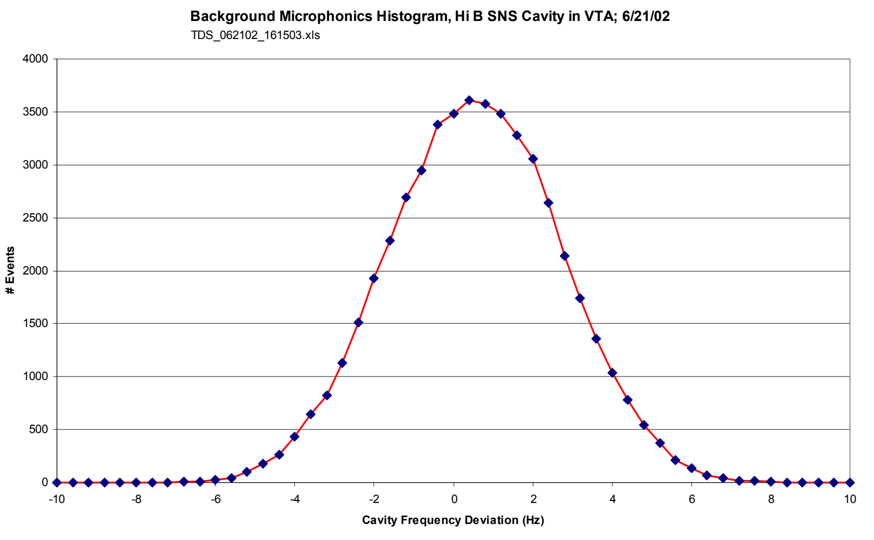
Cavity #2

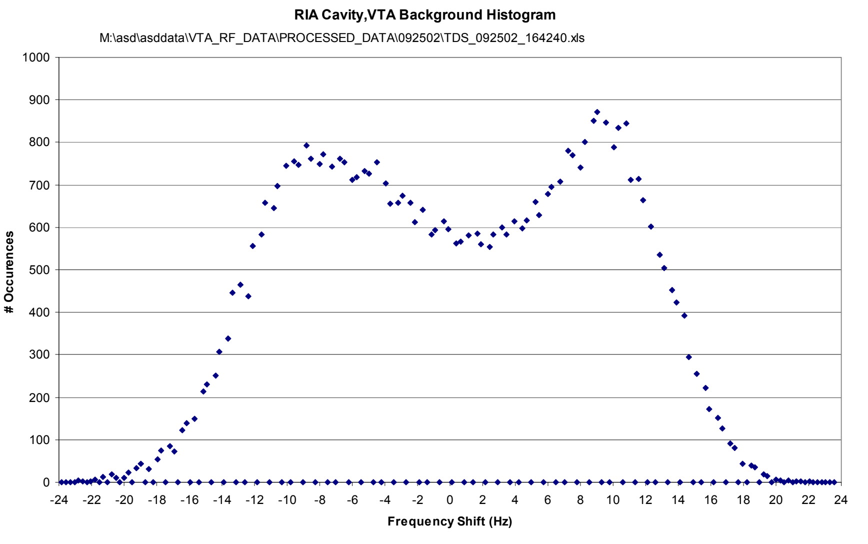
~3Hz rms

Cavity #1

~7Hz rms

Microphonics (probability density)



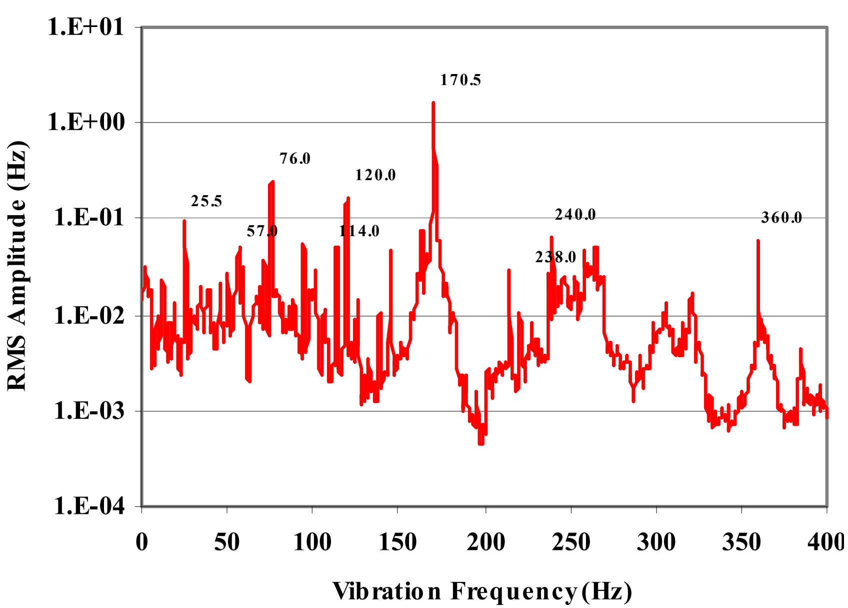


6-cell 805 MHz, β=0.82 in VTA

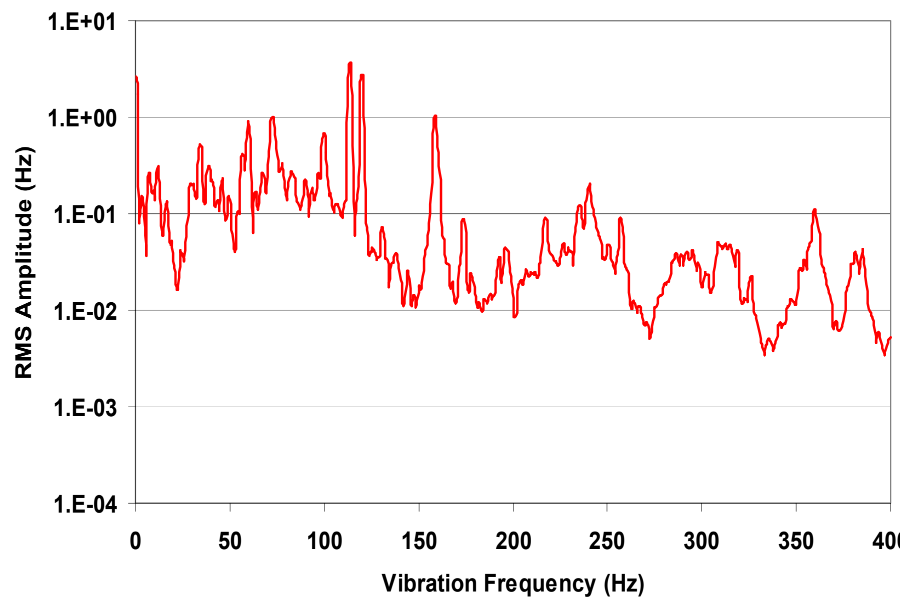
6-cell, 805 MHz, β=0.47 in VTA

Microphonics (frequency spectra)

Frequency spectra are different between cavities

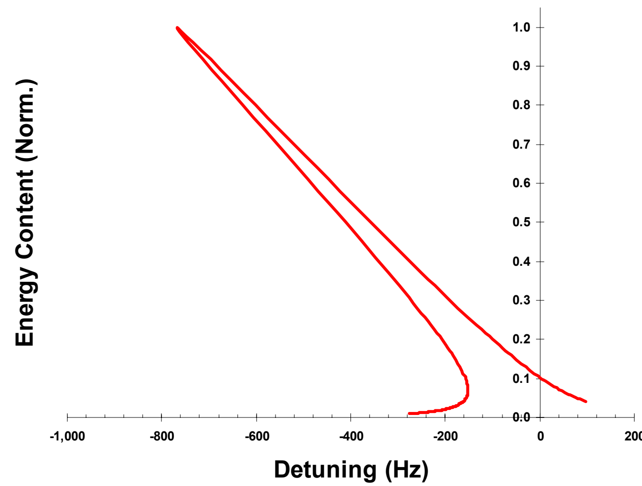


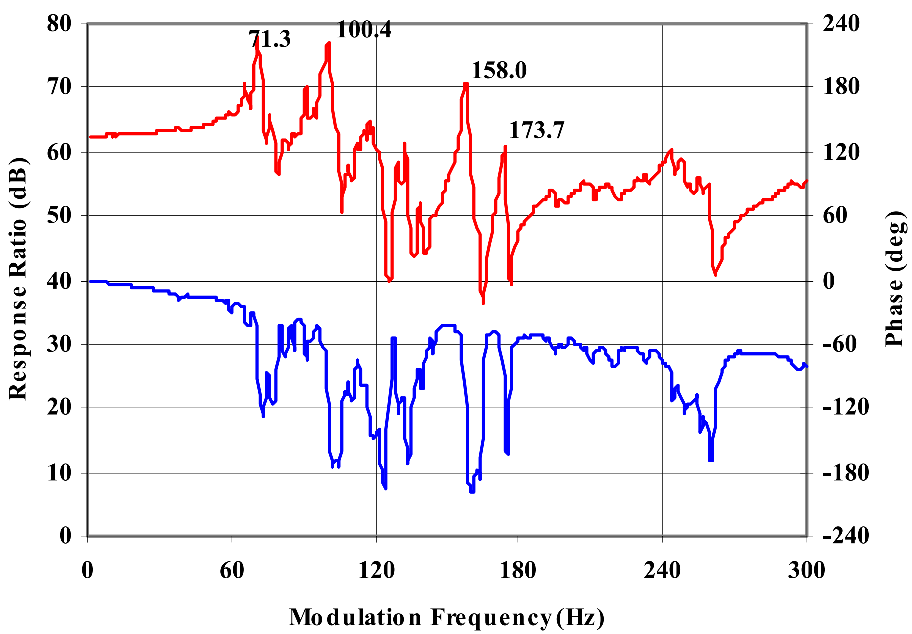
Cavity #2



Cavity #1

Ponderomotive Effects – Lorentz Detuning

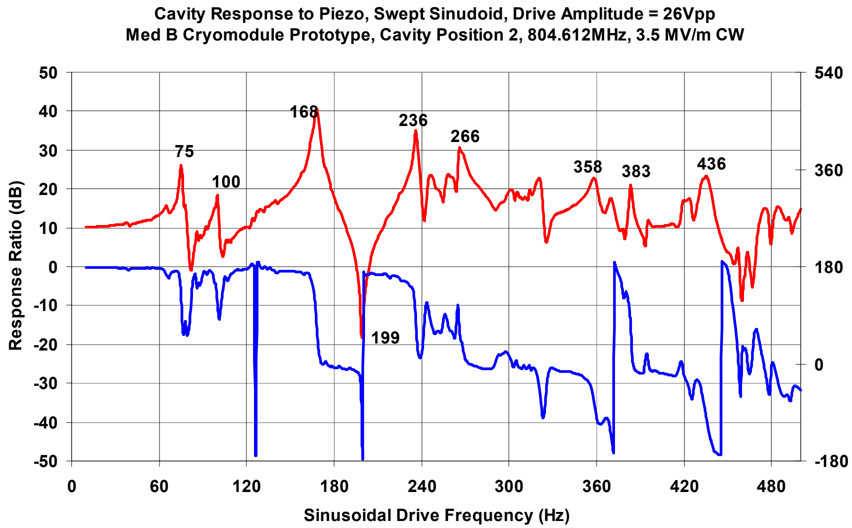


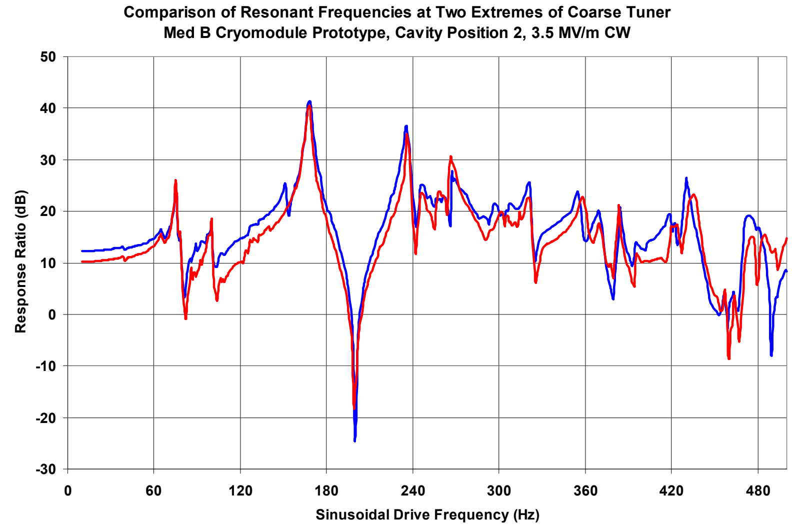


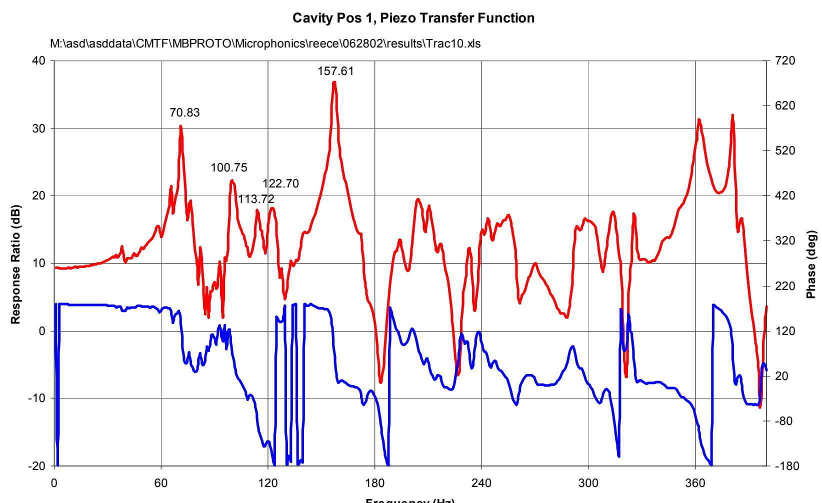
- Response of cavity frequency to small sinusoidal modulation of cavity rf field

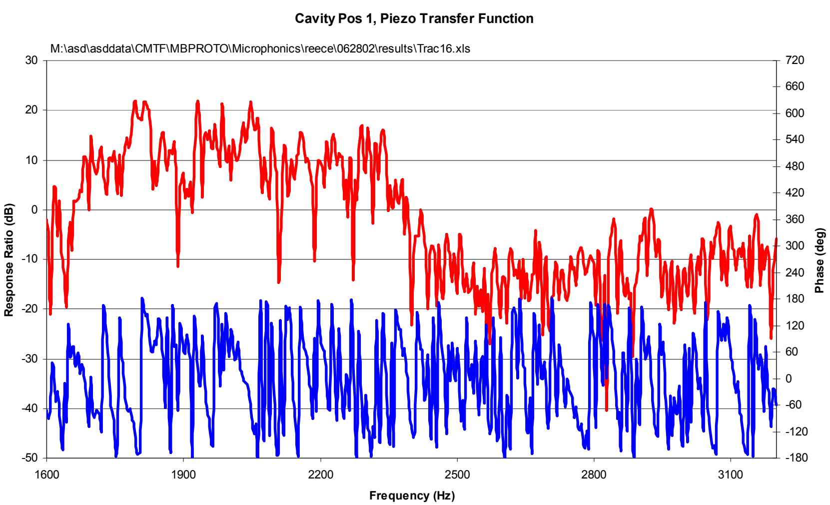
Cavity #1

Piezo-Driven Response









RF Power

$$P = \left(\frac{Q_0 + Q_{ext}}{4Q_{ext}}\right)\frac{E^2 l^2}{\frac{R}{Q} Q_{ext}}\left[\left(1+\frac{Q_{ext}}{Q_b}\right)^2 + \left(\frac{Q_{ext}}{Q_m}\right)^2\right]$$

with: $$Q_b = \frac{\omega U}{\text{Power absorbed by beam}} = \frac{El}{I \cos\phi_0 \frac{R}{Q}}$$

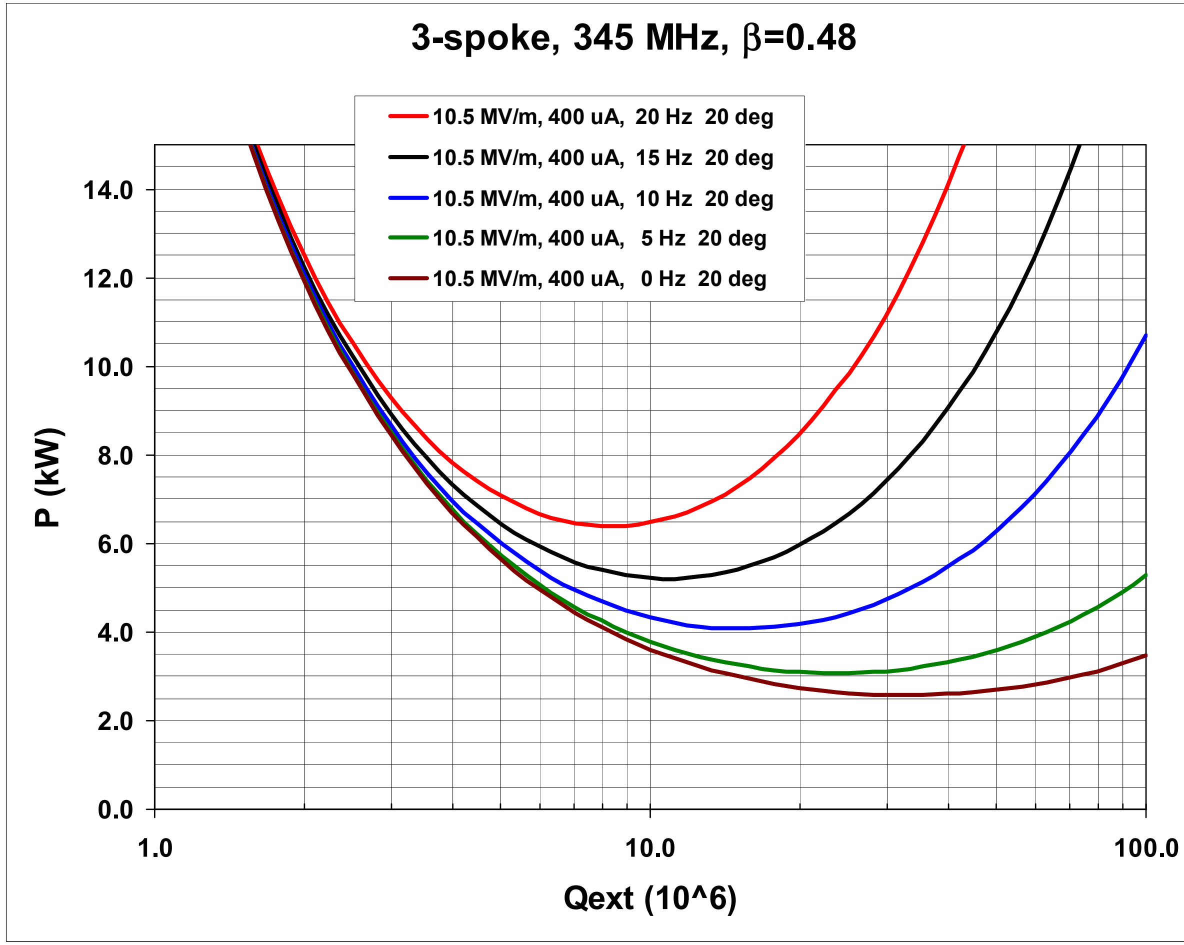
$$Q_m = \frac{\omega_0}{2\Delta\omega_d} \quad , \quad \Delta\omega_d = \Delta\omega_{static} + \Delta\omega_{microphonics}$$

$\Delta\omega_d$ is usually taken as twice tuner resolution plus 6 x rms microphonics

When $I = 0, \quad P_{opt} = U\Delta\omega_d$

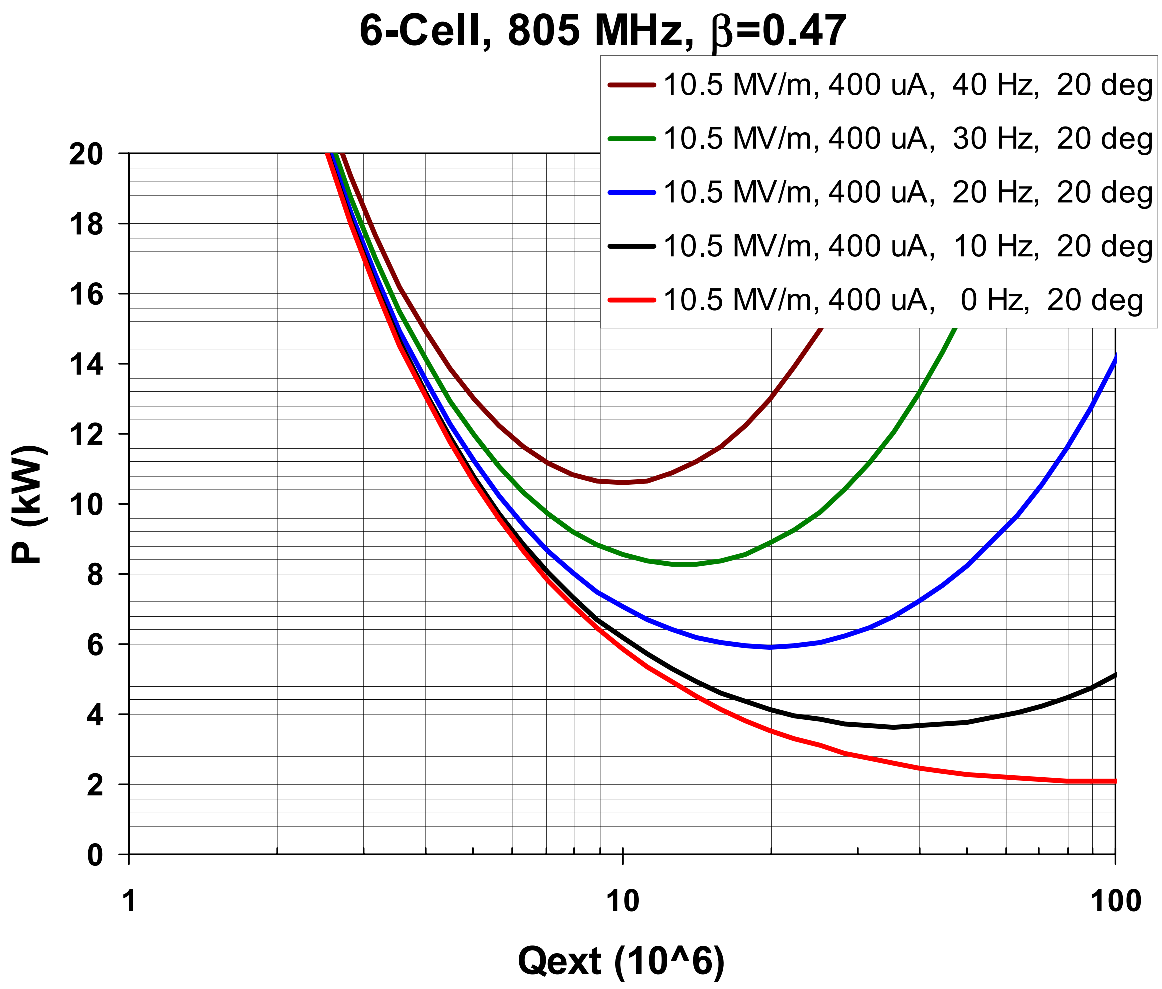
3-spoke, 345 MHz, β=0.48

6.82 MV



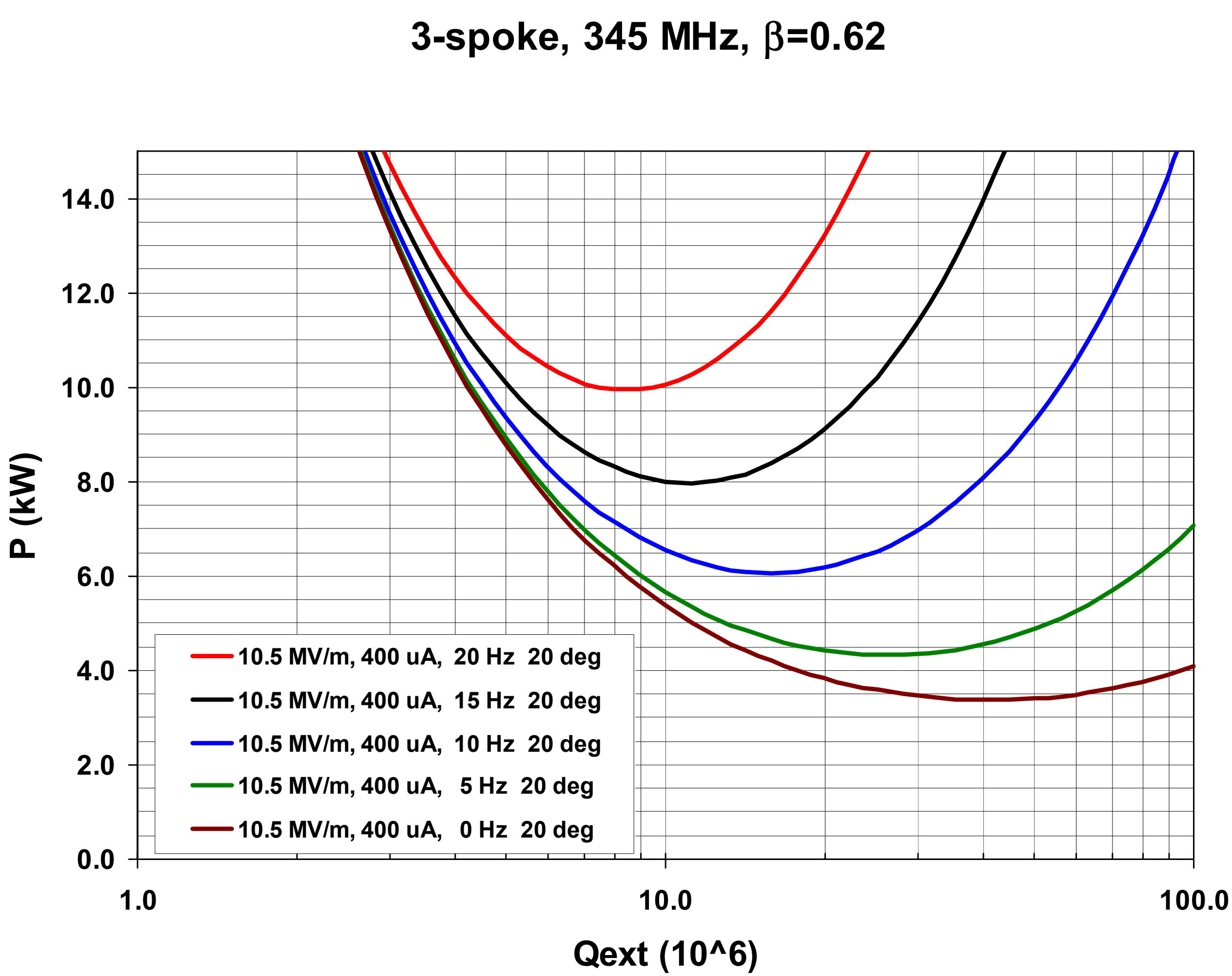
6-Cell, 805 MHz, β=0.47

5.53 MV



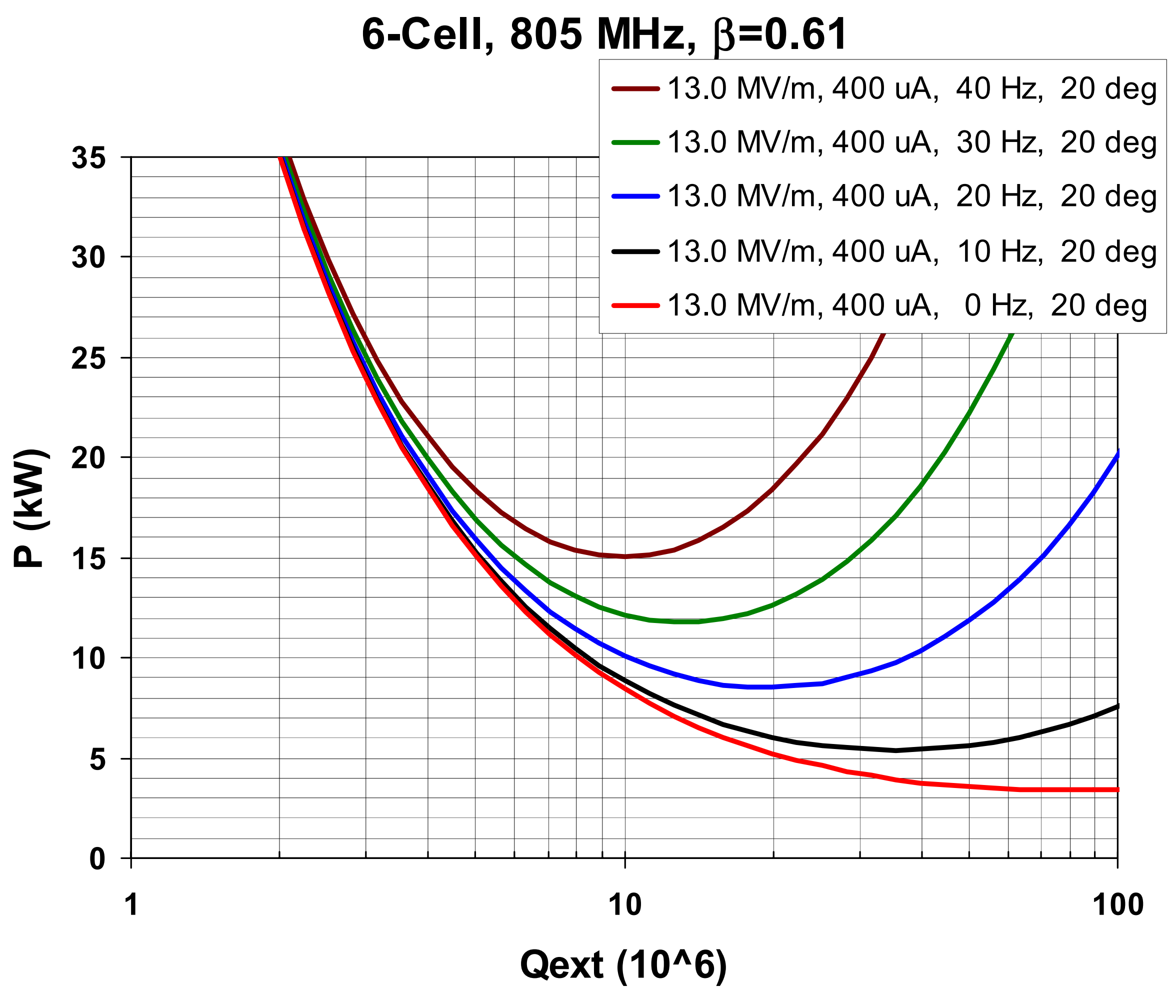
3-spoke, 345 MHz, β=0.62

8.9 MV

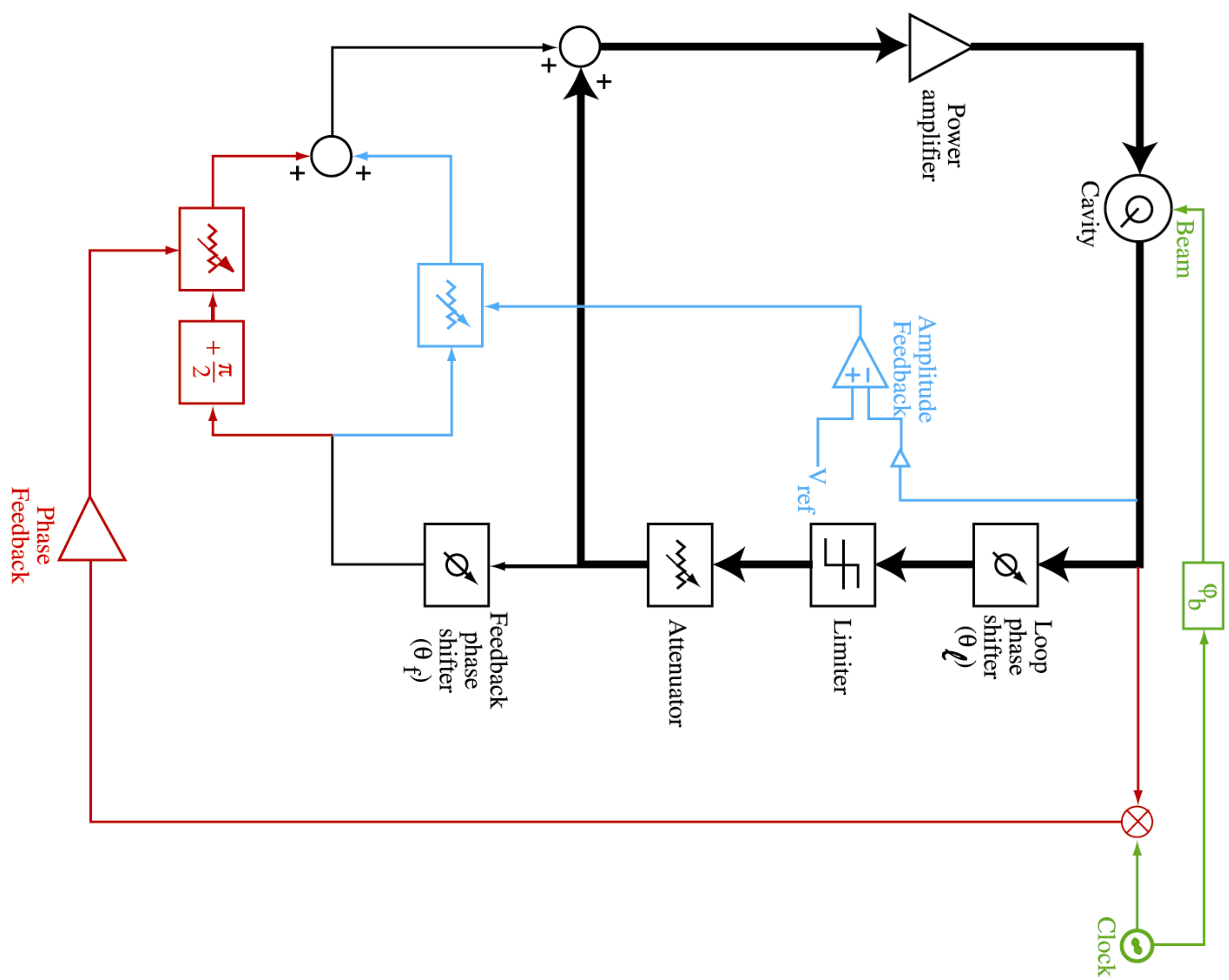


6-Cell, 805 MHz, β=0.61

8.9 MV



Negative Phase Feedback



Electronic Damping of Microphonics

Amount of modulation required to reduce frequency excursions by a given amount:

$$\frac{<\delta\omega_{ex}^2>}{<\delta\omega_c^2>} = K^2 \qquad K : \text{reduction factor}$$

$$<\delta\nu^2> = \frac{<\delta\omega_{ex}^2>}{4Q_\mu^2\left(k_\mu V_o^2\right)^2} \frac{\left[K^2-1\right]^2}{K^2}$$

If $\quad <\delta\omega_{ex}^2> = \left(2\pi\times 5\right)^2 = 1000$

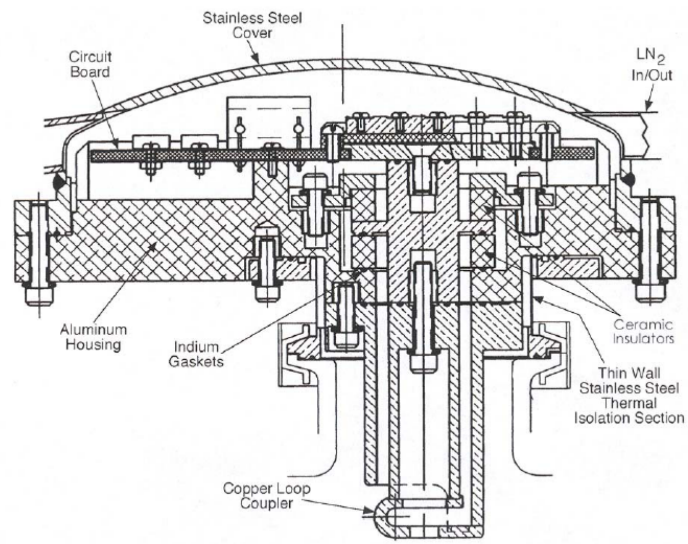
$$\left(k_\mu V_o^2\right)^2 = \left(2\pi\times 300\right)^2 = 4 \;\; 10^6$$

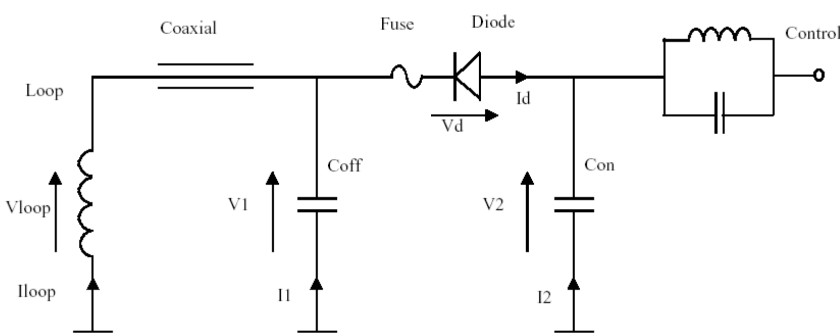
$$\left(2Q_\mu\right)^2 = \left(2\times 2\pi\times 100\times 0.25\right)^2 = 10^5$$

for $\quad K = 2 \qquad <\delta\nu^2> \;\simeq 0.5 \;\; 10^{-8}$

Voltage-Controlled Reactance

- Has been successfully applied at lower frequencies
- Unlikely to be applicable at the frequency and power levels for TM_{010} cavities





Discussion on "Controls - Overview" by Jean Delayen

Delayen gave on overview on controls for systems like CEBAF and SNS (elliptical cavities at 2K). While these machines have well defined operational parameters, a multi-species and multi-target machine like RIA has a much wider range of scenarios that need to be provided and controlled. Shepard pointed out that a tuning accuracy of 2*tuner sensitivity + 6*microphonics bandwidth is not applicable for RIA. They aim at 2*tuner sensitivity + 20*microphonics bandwidth. Their main concern is strongly deviating behavior of components, not the behavior of the average machine.

Shepard also mentioned that the existing experience with microphonics behavior is not applicable for RIA: RIA is a machine with "soft" bulk niobium structures operated at 4K, using forced flow in the cryo-system. CEBAF experience does not apply due to the 2K operation, Legnaro's successful microphonics control work does not apply due to their much stiffer niobium on copper structures.

There was general agreement that the main issue to understand the microphonics issues of a system is the understanding of the interaction between the cryosystem and the RF-structures.

As a next point the different valuation of microphonics for different projects was expressed. A system like CEBAF can tolerate the loss of lock for a cavity once in a while. The tolerances need to be much tighter for RIA that cannot afford to loose lock at all (on a timescale of a few milliseconds). Availability requirements for all these machines are driven by the tolerable thermal fluctuation in the beam targets. Delayen expressed that the target requirements for any machine need to be well understood upfront, for both being to conservative in tuning control, or being to aggressive can be costly.

Pagani made a general comment the microphonics issues of a system are driven by boundary conditions. The same object (e.g. resonator) can be working in one environment and not at all in a different one. Boundary conditions like helium temperature can change the response completely. His conclusion is that each setup of cavities, external components, cryosystem, ... needs to be studied separately. He also claimed that elliptical cavities are more easily controlled, as there is a simple way to control frequency and phase of the RF-input. Delayen expressed that he does not see any advantage of the ellipticals, as all microphonics responses of a system are driven by mechanical waves that have the same time delay issues to influence a full structure.

Delayen reported that Jlab is looking at a novel way to control cavity tuning by ferrite in the waveguides feeding power couplers. They see the potential for a fast active control of microphonics to reduce the control margin needed for cavity operation e.g. for SNS. It was agreed that could be an important contribution to the field.

Pagani summarized the problematics of microphonics. At the origin of microphonics are mechanical phenomena. The effect that needs to be dealt with is, is the behavior of the RF in the cavities. The transfer mechanism is complex. It affects both the behavior of the fundamental as the higher order modes. Since even identical resonators do not have an identical RF-behavior over all modes, the responses show the wide spread reported here.

Microphonics Measurements in Spoke Cavities

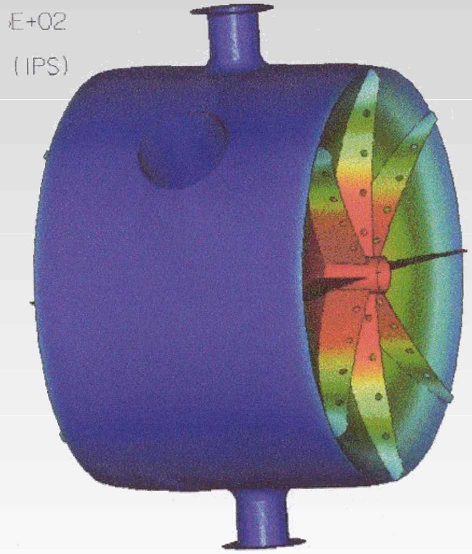
M. Kelly, Argonne National Laboratory

Phase stabilization of the RIA drift-tube cavities in the presence of micrphonics will be key for RIA. Tests on the beta=0.4 single-cell cavity, including some with a new "cavity resonance monitor" to measure microphonics, verifty that the spoke cavity is a particularly stable structure with respect to both microphonics and Lorentz detuning.

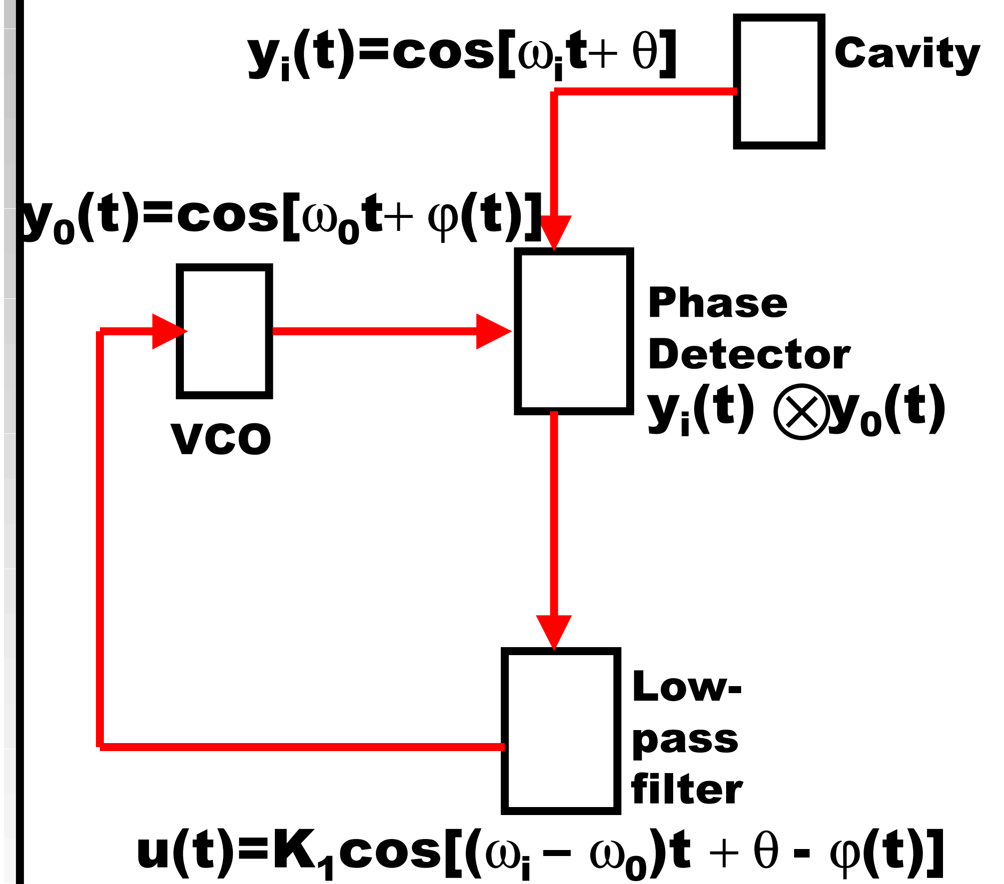
Microphonics Measurements in Spoke Cavities

Overcoupling + Negative Phase Feedback or Voltage Controlled Reactance?

- **Phase-locked loop; Cavity Resonance Monitor**
- **Phase noise**
- **Measurements**



Phase-locked loop



Ref. - A. Blanchard, Phase-locked Loops, 1976

Cavity Resonance Monitor

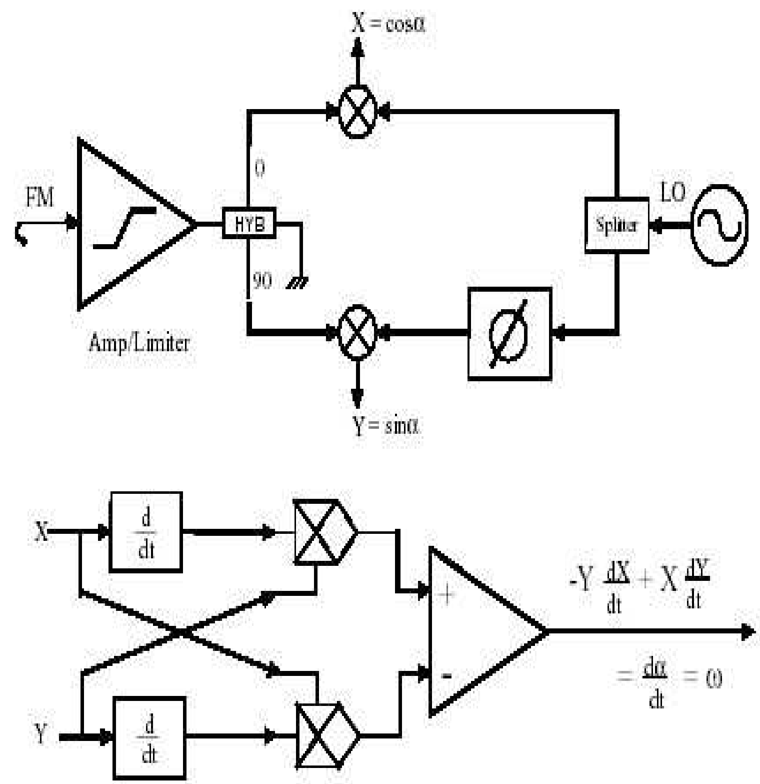


Figure 1: Cavity Resonance Monitor Block Diagram

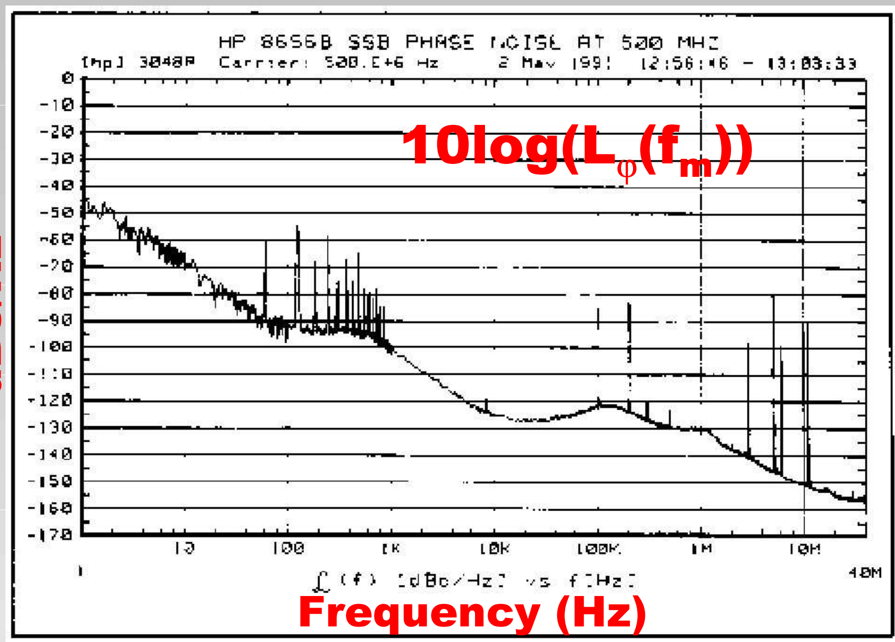
G. Davis, J. Delayen et. al., PAC 2001

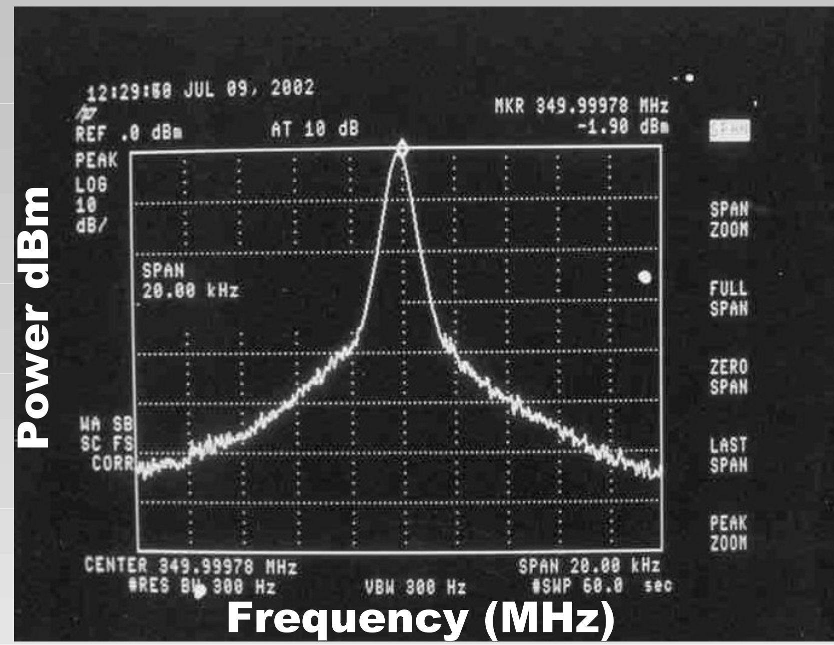
Cavity Resonance Monitor

Sergey Sharamentov sharamentov@phy.anl.gov

Phase Noise ⟷ Frequency Modulation

dBc/Hz





$$y_i(t) = \cos[\omega_i t + \varphi \sin \omega_m t]$$

φ is the peak amplitude of phase modulation for a modulating frequency ω_m

Cavity frequency = $\omega_i + \omega_m \varphi \cos \omega_m t$

$$\boxed{\omega_{peak} = \omega_m \varphi}$$

Frequency Modulation from Phase Noise

$$\omega_{peak} = \omega_m \varphi$$

Relates peak freq. modulation to peak phase modulation

$$S_f(\omega_m) = \omega_m^2 S_\varphi(\omega_m)$$

Power density of freq. oscillation vs. phase oscillations

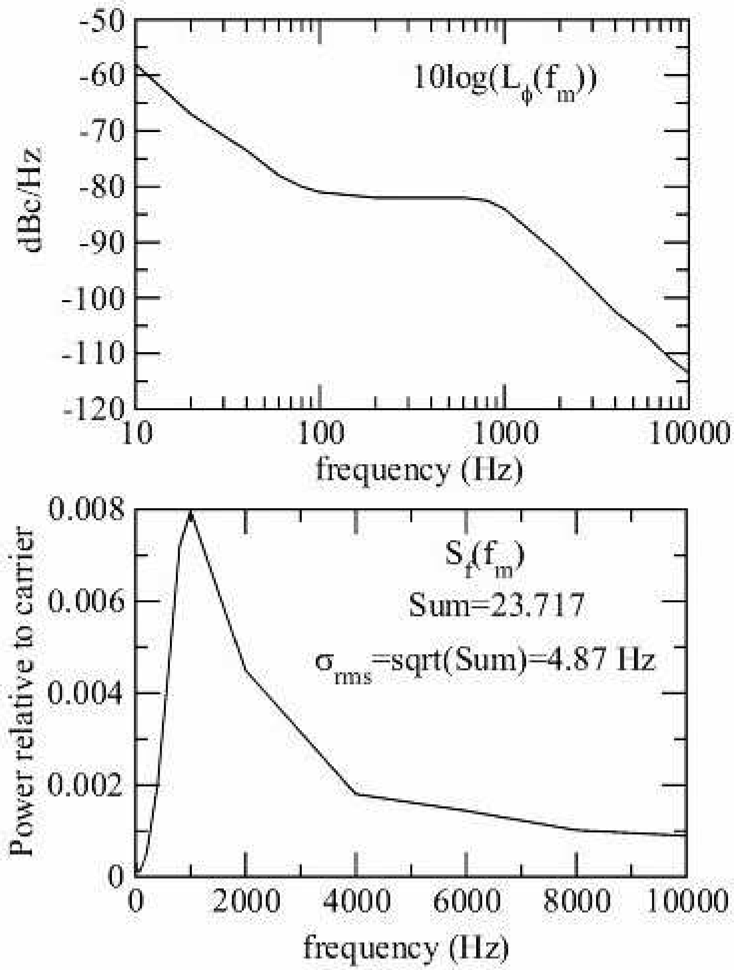
or

$$S_f(f_m) = f_m^2 S_\varphi(f_m)$$

$$\sigma_f = \sqrt{\int_{f_1}^{f_2} S_f(f_m)\, df_m}$$

RMS frequency deviation

HP 8656B FM from Phase Noise Spec

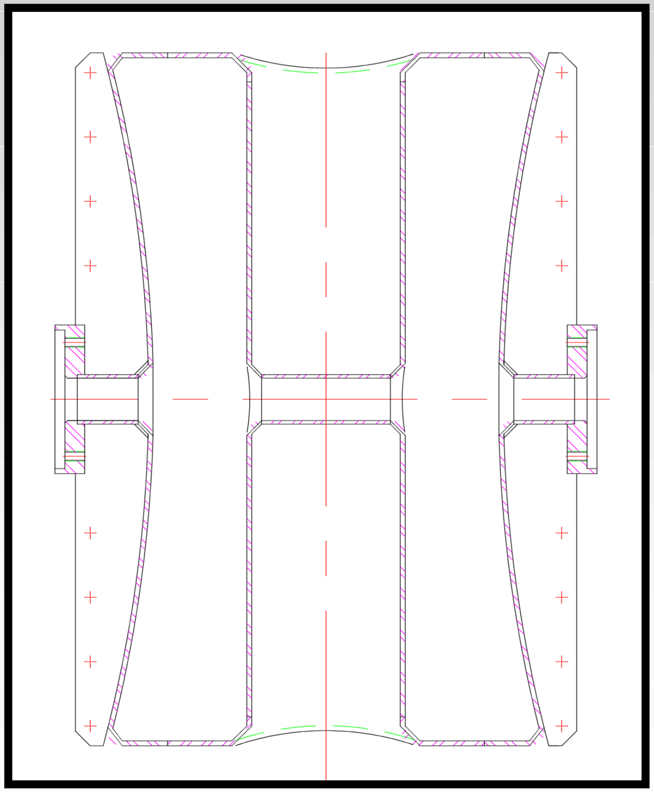


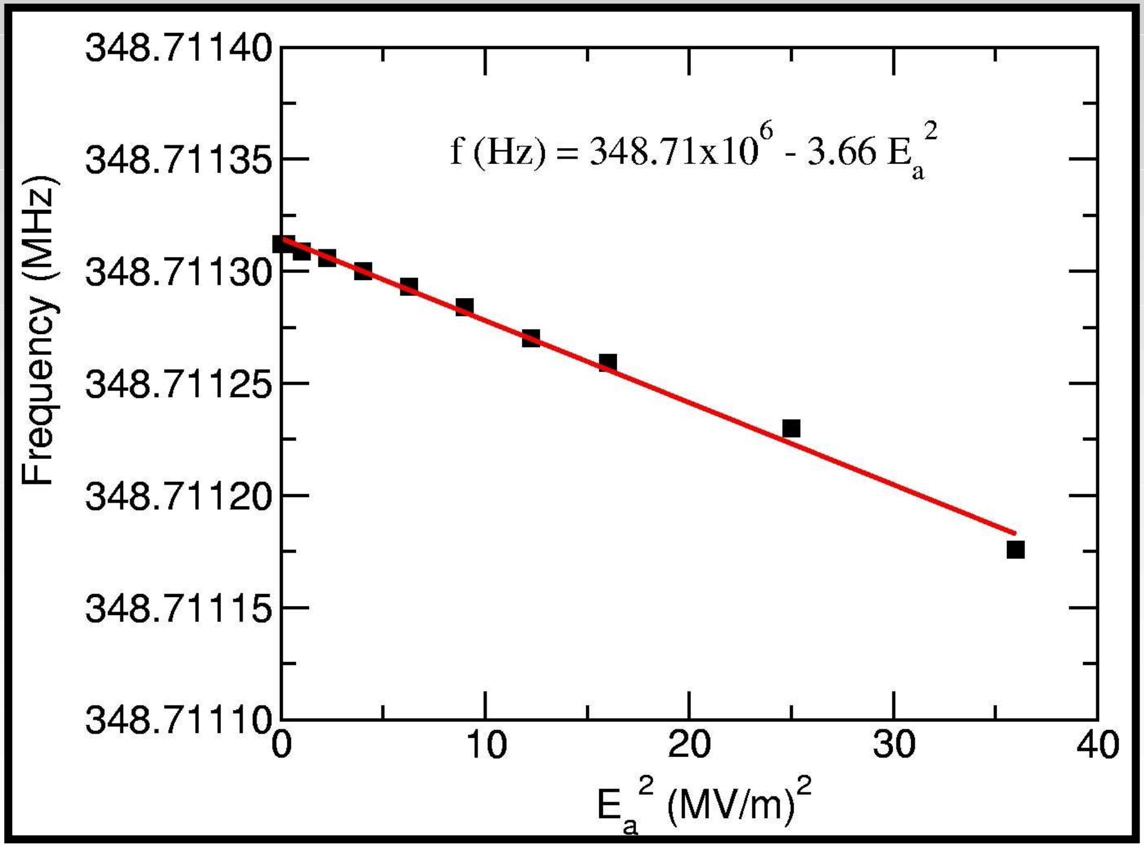
Actual Measured value From error signal ~ 15 Hz Due to spurs at line frequency

Agilent 8665 about factor of 10 better

Some β=0.4 Spoke Cavity Mechanical, EM Properties

- Stored Energy 82 mJ, E_{PEAK}=4 MV/m, B_{PEAK}=107 G at E_{ACC}=1 MV/m
- Active length 23 cm
- RRR~150, ~2.8 mm average thickness after processing
- Pressure sensitivity 120 kHz/atm at 4 K (~10% higher warm)
- Lorentz detuning 3.7 Hz/$(MV/m)^2$





Low-lying acoustic modes from FEA (J. Fuerst)

Spoke moving in and out

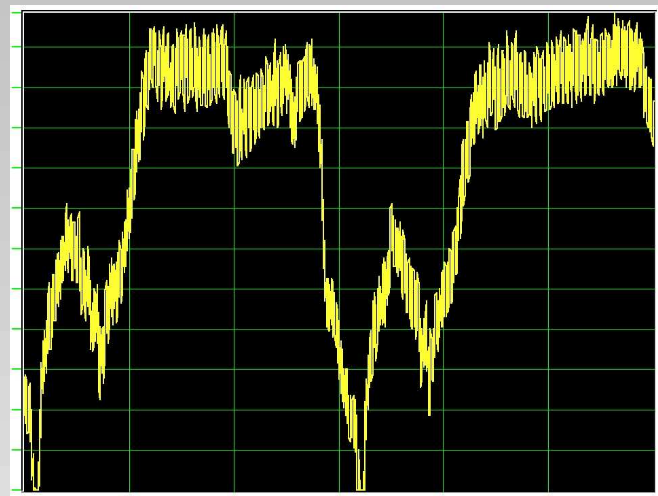
End wall vibration

Beam port vibration

Mode			**Frequency** (Hz)
1			259
2			279
3			315
4			360
5			398
6			422
8			461
11			488
16			723
17			727

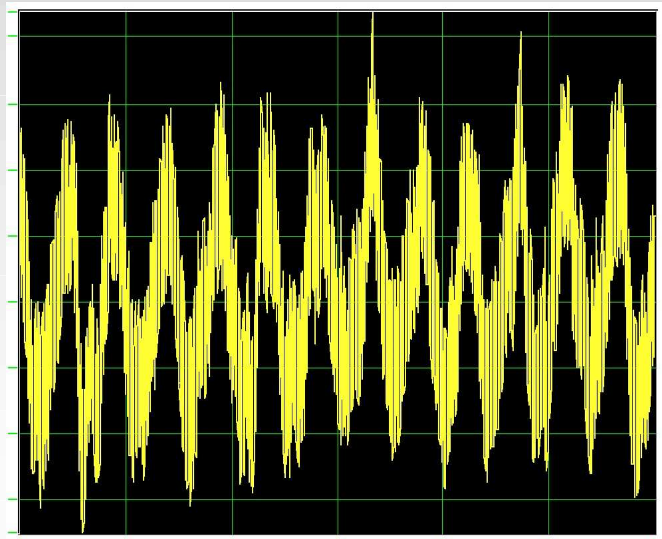
Refrigerator Effects: PLL Error Signal 6/28/02

Δf = 1150 Hz



2800W refrigerator set up with 2 watts excess capacity with 1S loaded at 2800 rpm and 8S unloaded. L dewar pressure 2.4 psig

Δf = 280 Hz

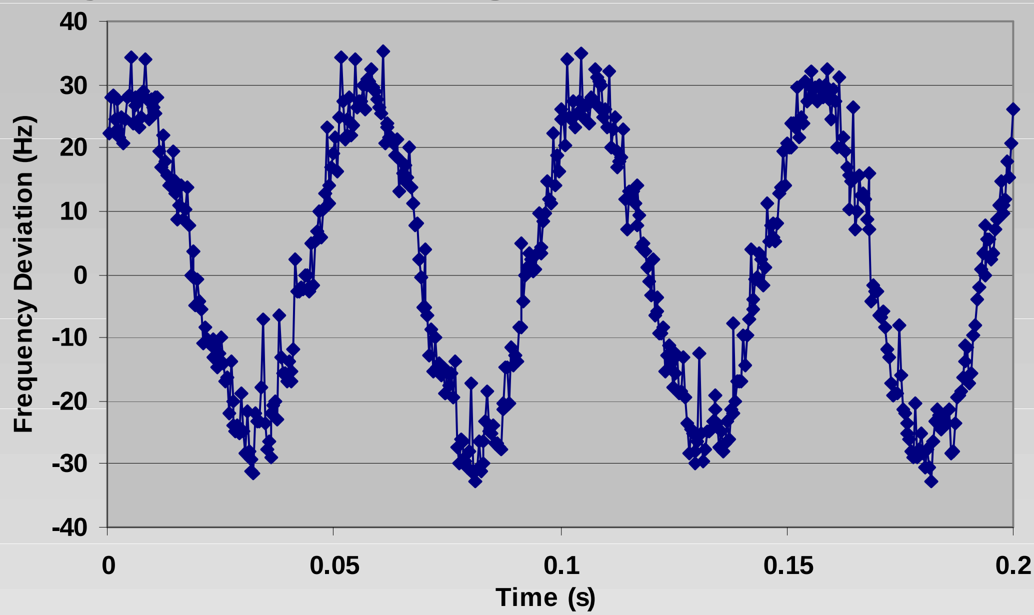


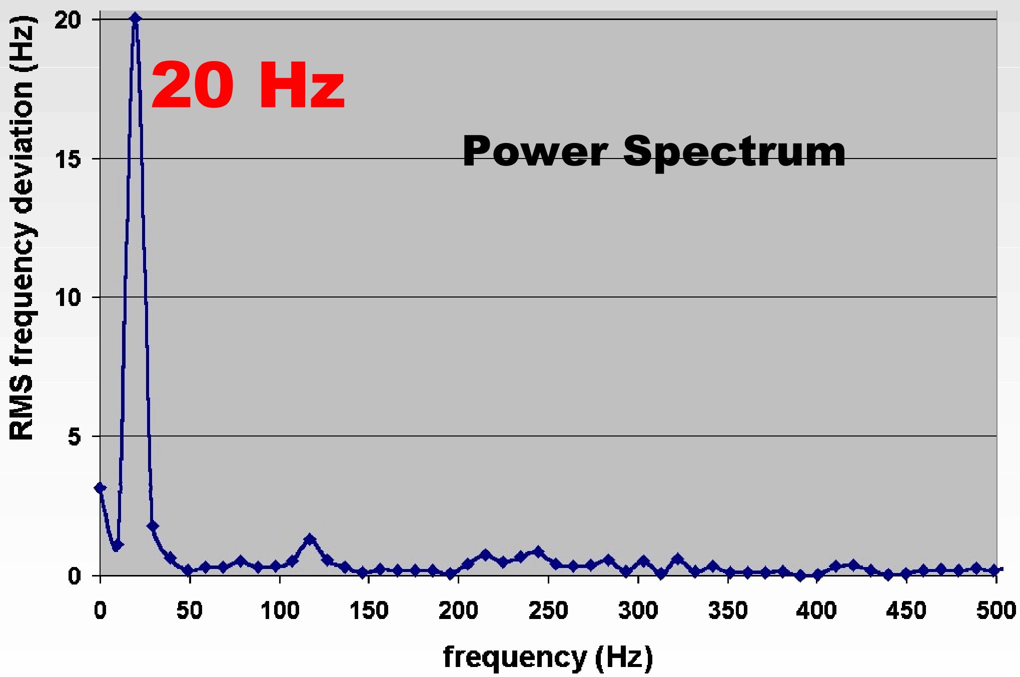
Refrigerator conditions are 60 watts excess capacity. L pressure = 2.8 psig. 1S loaded at 3600 rpm & 8S unloaded.

300 seconds

Spoke Cavity PLL Error Signal: Thermal-acoustic oscillation

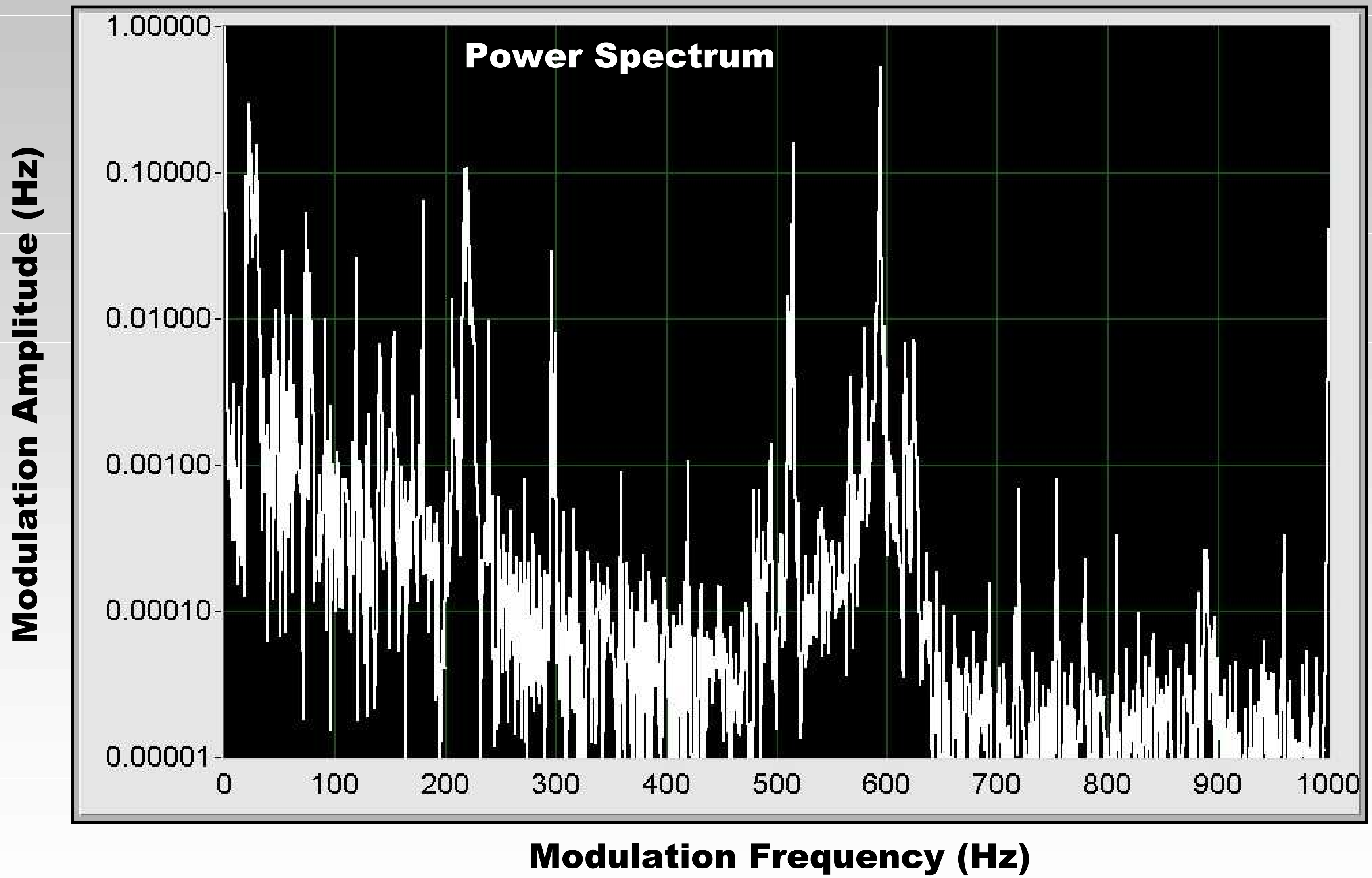
6/24/02



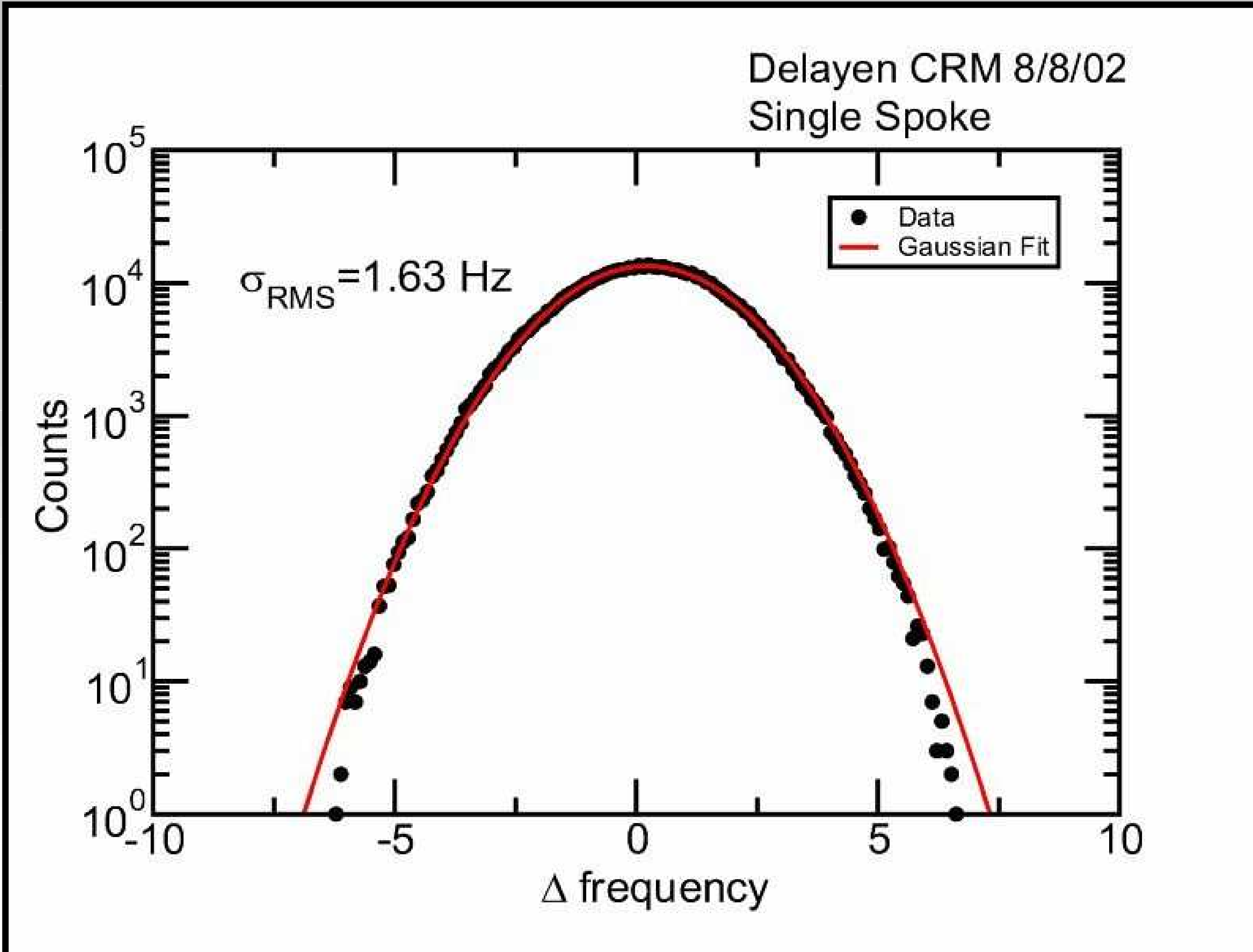


ANL Physics Division

Single Spoke w/ Cavity Resonance Monitor 8/8/02



Single Spoke w/ CRM: 50 sec. At 11 kHz



Discussion on "Microphonics Measurements in Spoke Cavities" by Mike Kelly

The interpretation of the ANL microphonics data shows that the understanding of the cryoplant parameters is very important for the severity of this effect. The data taken with the cryosystem connected to the cavity test cryostat clearly showed cryoplant driven effects that are not seen when the system is disconnected.

In the further discussion on the issue of "loosing lock" due to microphonics it became clear that high mechanical resonance frequencies help a lot to reduce the impact of microphonics. A control system can recover (unnoticeable to the beam delivery onto the target) quickly from deviations of the tuning window, if the phase error to be corrected is small. High frequencies of the mechanical resonances mean short time periods of detuning and thus small accumulation of phase error.

On the applicability of these ANL measurements to the real accelerator Kelly pointed out that the test cryostat is a good replica of the real cryostat. The cavities are already tested in horizontal orientation in a horizontal cryo-vessel. Many of the auxiliary components and fixtures resemble the components that would be used in operation.

Power Couplers

Brian Rusnak: "*Power Coupler Design for RIA*"
(Abstract | Viewgraphs | Discussion)

Frank Krawczyk: "*Design of a Power Coupler for the AAA Spoke Resonators*"
(Abstract | Viewgraphs | Discussion)

Power Coupler Design for RIA

B. Rusnak, Lawrence Livermore Laboratory

The RIA Driver Linac will require a large number of independently-phased RF cavities to efficiently accelerate beams spanning protons to uranium. The need for 265+ RF couplers spanning 57.5 - 345 MHz encourages developing coupler designs that have are broadband and can share parts to help reduce design and manufacturing costs. Power levels, adjustability options, multipacting levels, and other aspects of the design space shall be discussed.

Power Coupler Development for RIA

Spoke Cavity Workshop - Los Alamos National Lab
October 7-8, 2002
Brian Rusnak

Lawrence Livermore National Laboratory
Making History
Making a Difference
1952-2002

Proposed RIA Window/Coupler Design Philosophy

Lawrence Livermore National Laboratory
Making History Making a Difference
1952-2002

- Mechanical - even a modest coupler needs to be reliable
  - Use common components and geometries to reduce costs
  - Use brazed ceramic windows, Conflats, and VCR fittings over indium wire
  - Design for a warm window to avoid a secondary gas barrier
- RF/Electrical - becomes important if coupler size gets quite small
  - Avoid bellows in RF transmission line to narrow MP resonance bands
  - Design voltage handling of coupler geometry to handle 100% of the full standing wave power levels anticipated for an infinite VSWR condition (4x travelling wave power)
- Thermal - this is a CW coupler
  - Design with a thermal margin of ~200% at nominal operating VSWR
  - Use conductive cooling to thermal intercept circuit where possible to simplify design

RIA Power Coupler Requirements are Tied to Microphonic and RF Architecture Issues

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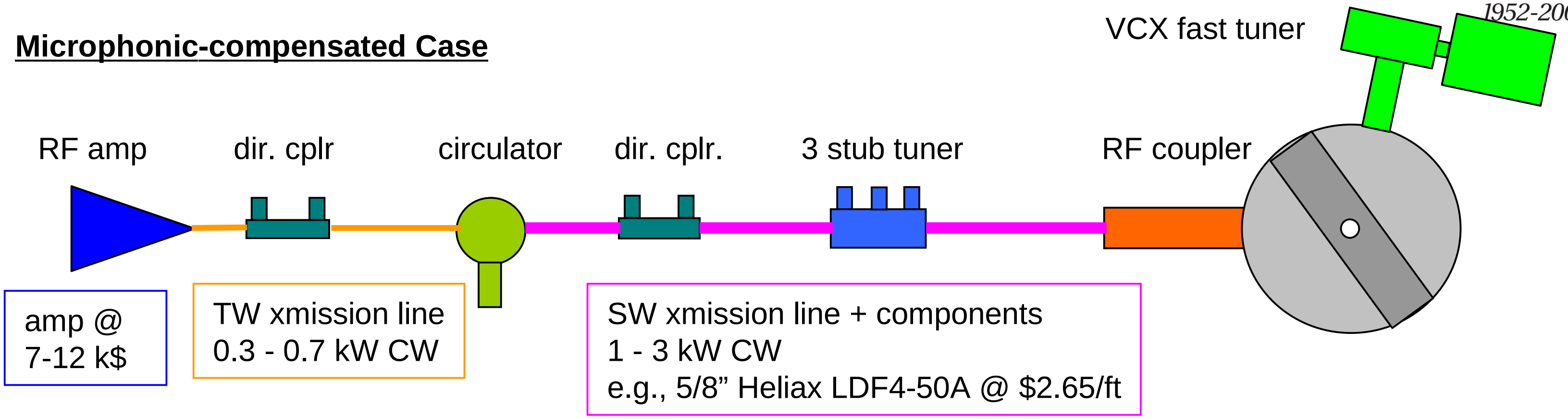
Making History Making a Difference
1952-2002

	numbers needed	frequency range	CW travelling wave (W)	CW standing wave (W)	operating VSWR	coupling approach
compenated micorphonics						
low β driver	276	57.5 - 345 MHz	350 - 700	1,400 - 3,000	1.7	magnetic
high β driver	140	805	2,000 - 6,000	8,000 - 24,000	1.5	electric
overcoupled approach						
low β driver	276	57.5 - 345 MHz	1,000 - 3,000	4,000 - 12,000	5 - 22	magnetic
high β driver	140	805	12,000 - 25,000	48,000 - 100,000	16 - 20	electric

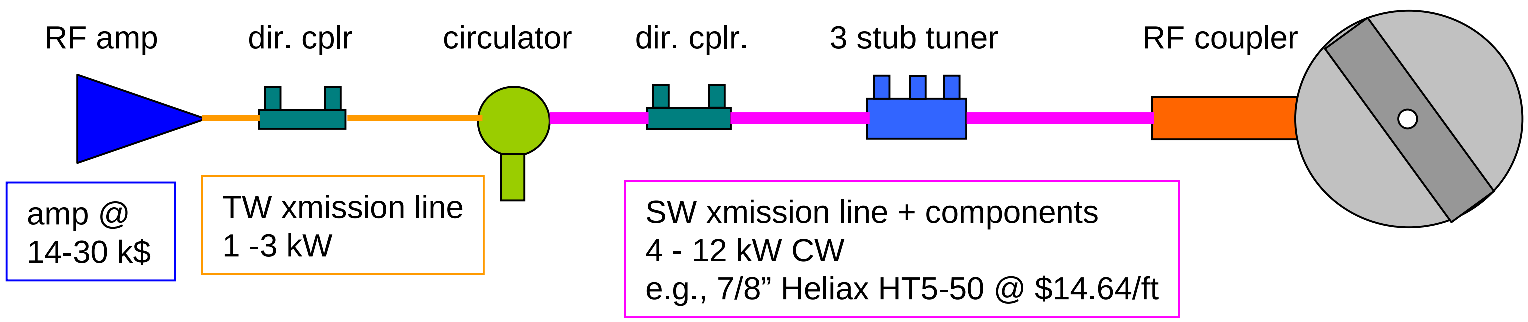
- Reduced (by stiffening) or compensated (by VCX) microphonics allows a smaller RF coupler to be used than the overcoupled case
  - for the low-β driver, the coupler is smaller by a factor of ~3 - 4
  - for the high-β driver, the factor is ~4 - 6
- In addition, the larger RF power levels for the overcoupled case impact component cost and size throughout the RF system

Strawman Low-β RF Architecture Designs for RIA

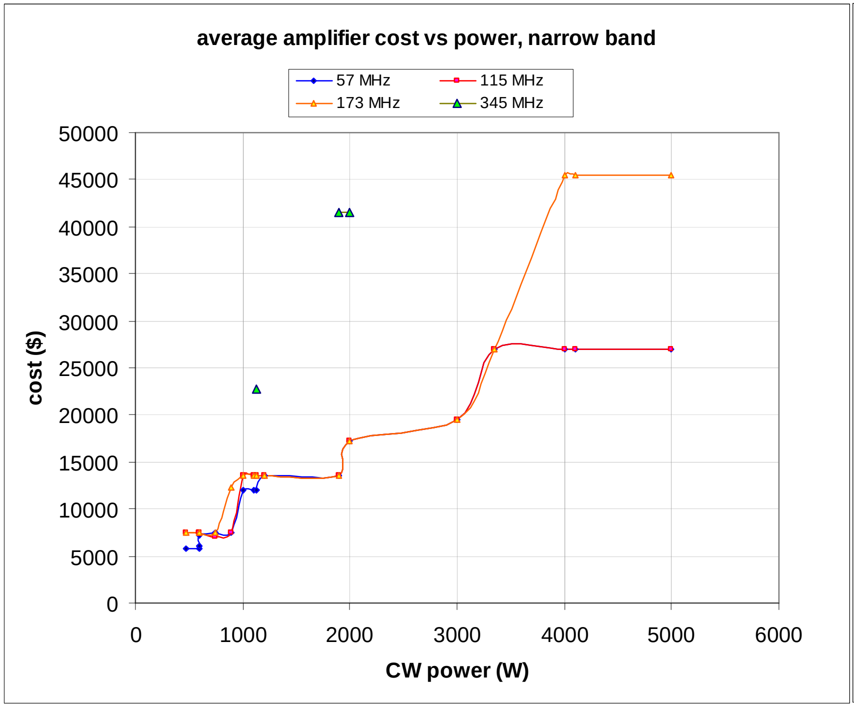
Microphonic-compensated Case

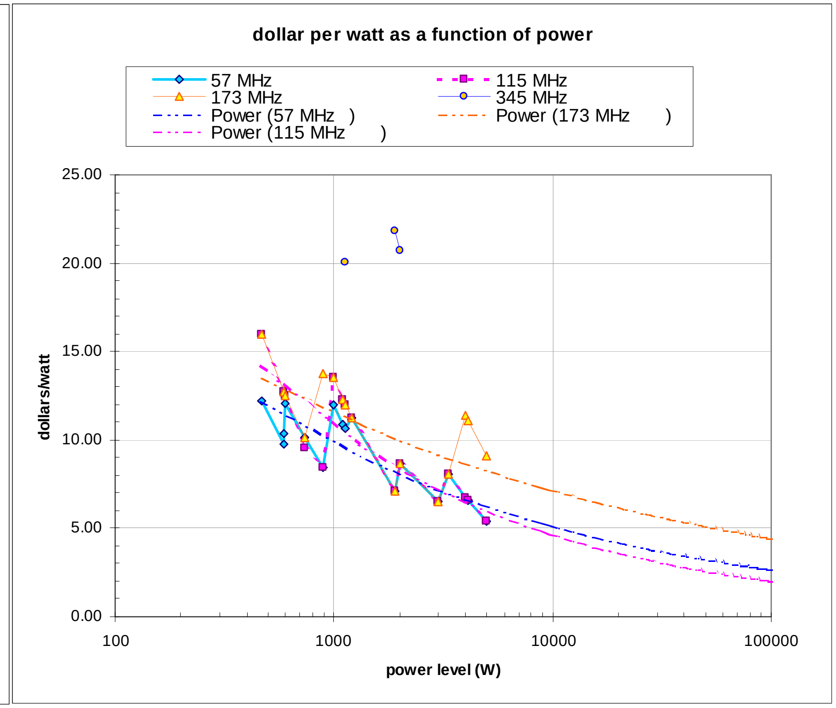


Overcoupled Case



RF Cost Data for Amplifiers, Low and High β Linacs

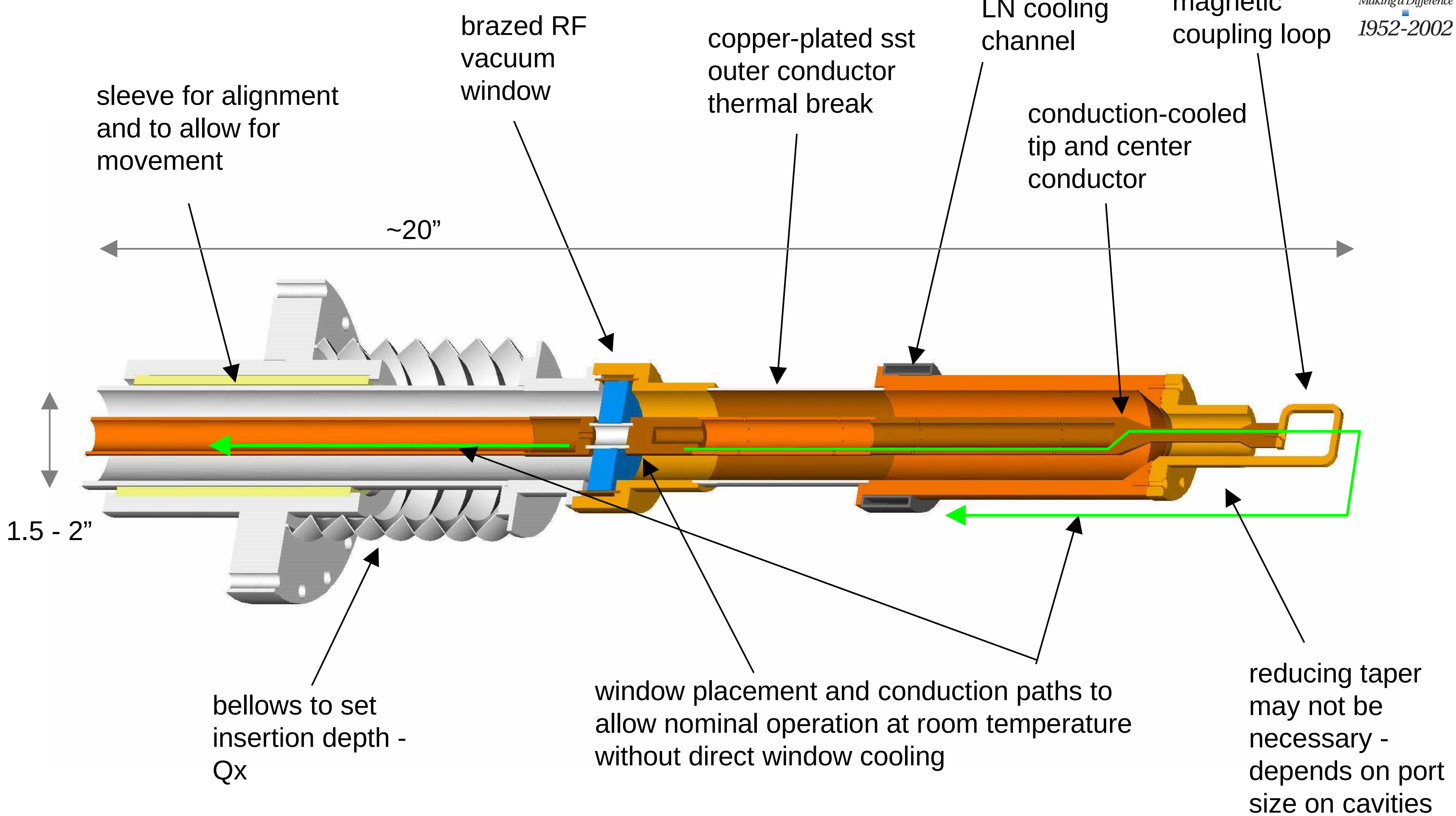




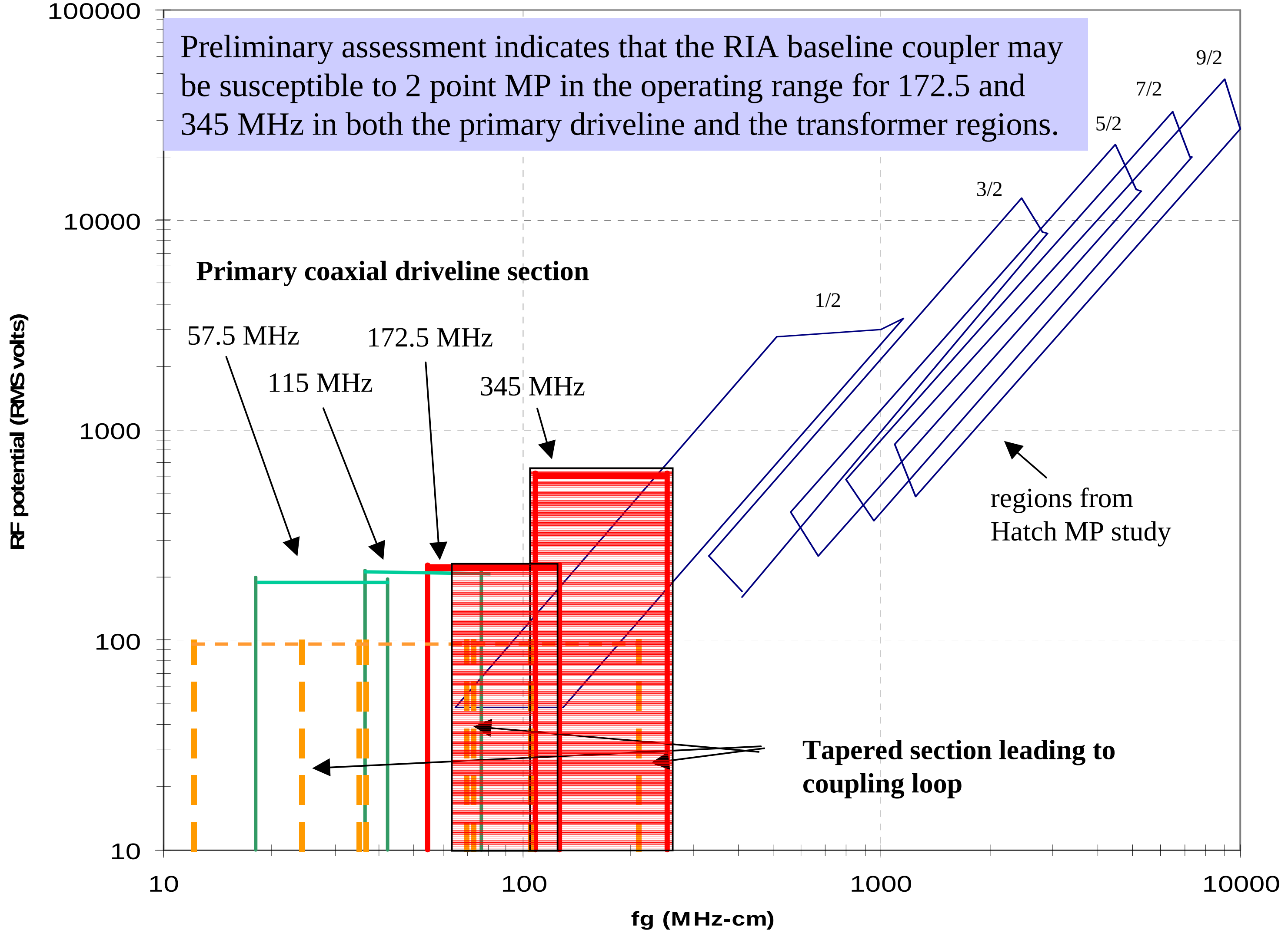
Data used to evaluate RF system costs for the low-β driver linac architectures

Extrapolated $/Watt numbers used to evaluate RF system costs for the high-β driver linac architectures

Baseline Design of an RF Coupler for the Low-β Driver Linac



Two Point Multipacting plot from: A.J. Hatch, "Supression of Multipacting in Particle Accelerators," NIM 41 (1961) pp. 261-277



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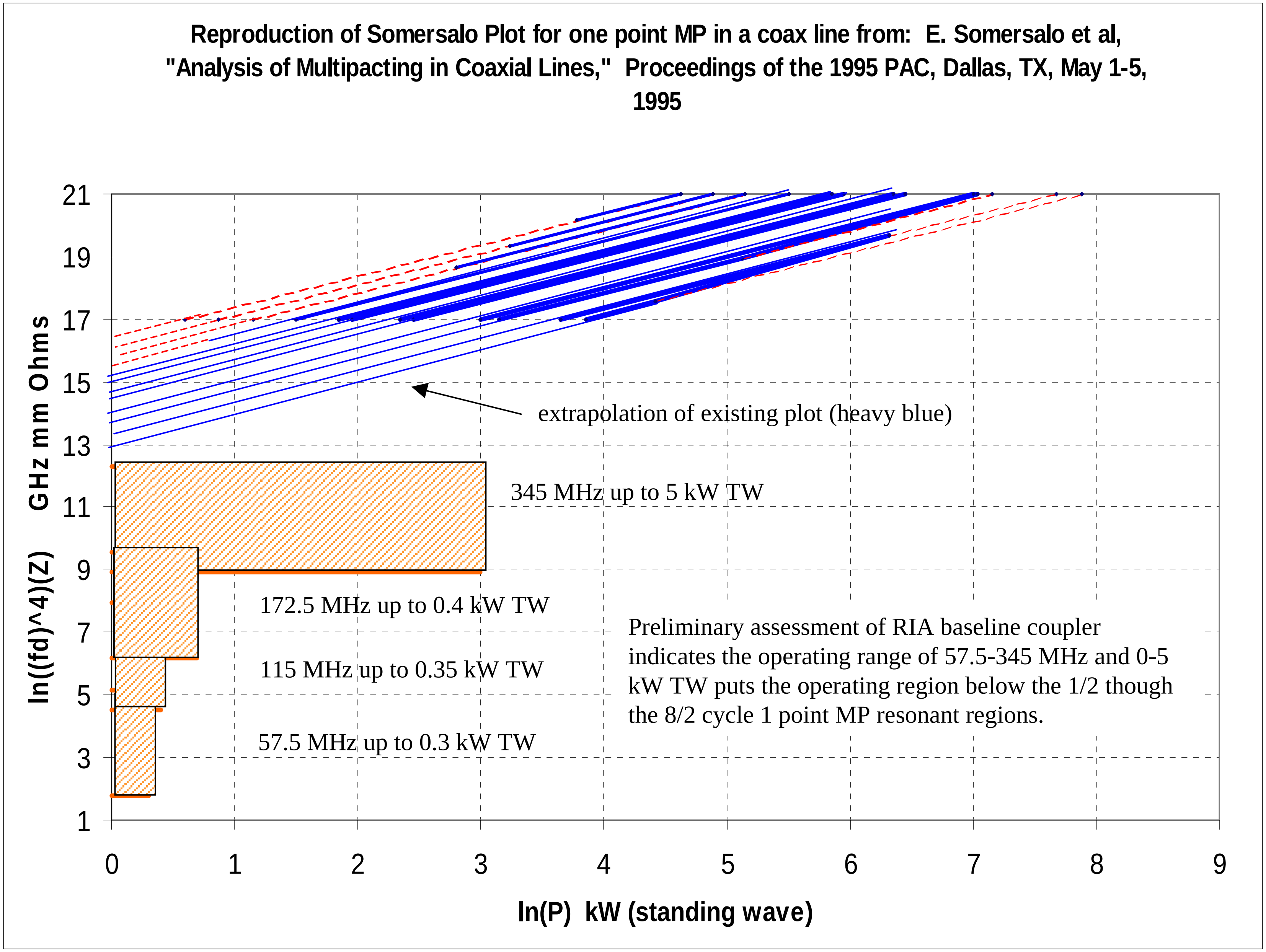
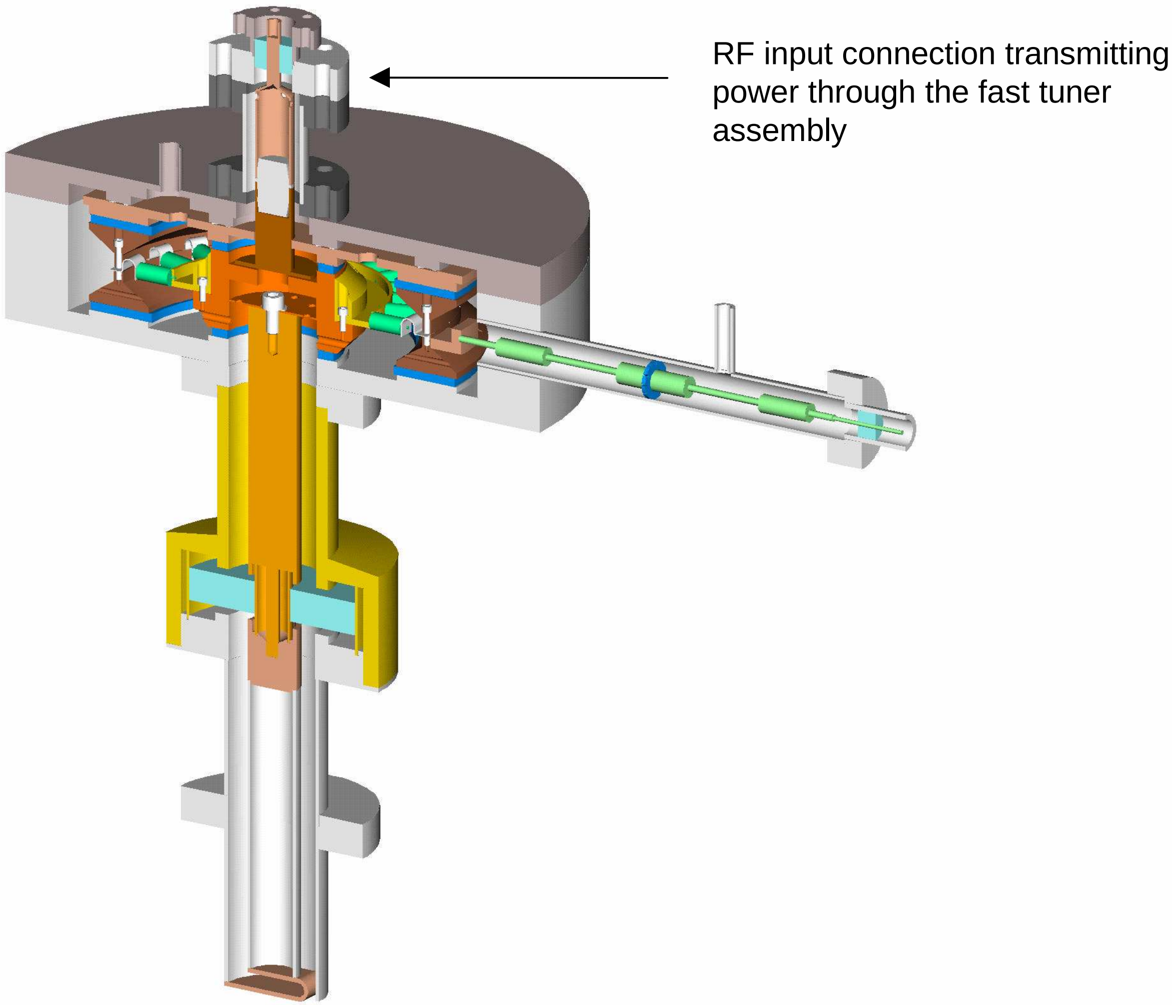
Making History Making a Difference
1952-2002


Reproduction of Somersalo Plot for one point MP in a coax line from: E. Somersalo et al, "Analysis of Multipacting in Coaxial Lines," Proceedings of the 1995 PAC, Dallas, TX, May 1-5, 1995
ln((fd)^4)(Z) GHz mm Ohms
ln(P) kW (standing wave)
extrapolation of existing plot (heavy blue)
345 MHz up to 5 kW TW
172.5 MHz up to 0.4 kW TW
115 MHz up to 0.35 kW TW
57.5 MHz up to 0.3 kW TW
Preliminary assessment of RIA baseline coupler indicates the operating range of 57.5-345 MHz and 0-5 kW TW puts the operating region below the 1/2 though the 8/2 cycle 1 point MP resonant regions.
21
19
17
15
13
11
9
7
5
3
1
0
1
2
3
4
5
6
7
8
9

It May be Possible to Incorporate the RF Drive into the Fast Tuner Assembly



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Open Questions (and Discussion Points) on the RIA RF Coupler

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- Since the power levels are reasonably low on RIA, is a 3 stub tuner be the best choice to achieve cost effective adjustability?
- Is making "one coupler fits all" the right approach for the low-β driver?
- What is the best common port size for the 4-6 cavities comprising the low-β driver linac? 1.5", 2", 2.5"...
- Is the SNS power coupler the best design for the RIA driver elliptical cavities?
  - The average power level is nominally right for TW operation (40 kW), but what about using a stub tuner, or handling mismatches?
  - Lighter beam loading will necessitate modifying the Qx set from SNS
  - How will CW vs. pulsed operation impact thermal intercept temperature choice and refrigerator efficiency?
  - Will saved NRE costs really compensate the technical compromises?

Discussion on "Power Coupler Design for RIA" by Brian Rusnak

Shepard commented on the issue of port size again. He agrees that there are nice features like easier processing that speak for large ports. He explained that RIA for the prototypes so far used 2 inches for it seemed adequate for the 5-10 kW power levels they expect to transmit. This statement is supported by the evaluation presented by Rusnak in this talk.

Rusnak added that for the 3-spoke resonator and for the kind of microphonics compensation selected this might have to be revisited. Shepard pointed out that this might require moving the RF-joint, where the coupler is attached to the cavity further out from the outer cavity dimension. This increases size and cost of the cryomodule. A trade-off might have to be done.

Design of a Power Coupler for the AAA Spoke Resonators

Frank Krawczyk, LANL

Beam apertures of spoke resonators require a direct coupling of the input power to the cavity volume. For low input power loop couplers for magnetic coupling are considered. Higher input power makes the thermal management of loop couplers in a cryogenic environment impractical. In our power coupler design work coupling by a coaxial antenna has been proposed and demonstrated. The baseline design for the coupler for spoke resonators at 350 MHz consists of a half-height WR2300 wave-guide section merged with a shorted coaxial conductor. At the transition is a 4.8-mm thick cylindrical ceramic window creating the air/vacuum barrier. The coax has a 103-mm outer diameter and an inner conductor matched to a 75-Ohm coaxial line impedance. The coax extends from the short through the wave-guide and terminates with an antenna tip close to the sidewall of the cavity. A full outer conductor diameter pumping port is located in the quarter-wave stub to facilitate good vacuum at the ceramic window. The coaxial geometry chosen is based on multipacting and thermal design considerations. The coupling coefficient is adjusted by statically re-setting the outer conductor length. The RF-physics design will be presented with emphasis on the interaction of the coupler with the cavity.

Design of the AAA Power Coupler for the β=0.175 Spoke Resonator

Frank Krawczyk
LANL

Workshop on the Advanced Design of Spoke Resonators

Los Alamos, NM, USA
October 7 and 8, 2002

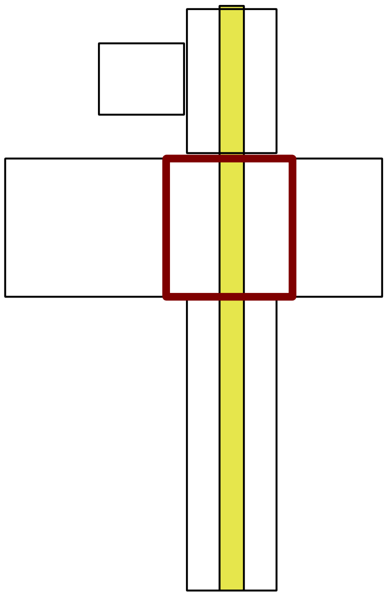
Introduction

- Special considerations for spoke couplers
- Geometry choice
- Multipacting considerations for sizing the coaxial line
- RF parameters for optimized coupler
- Peak fields
- RF losses

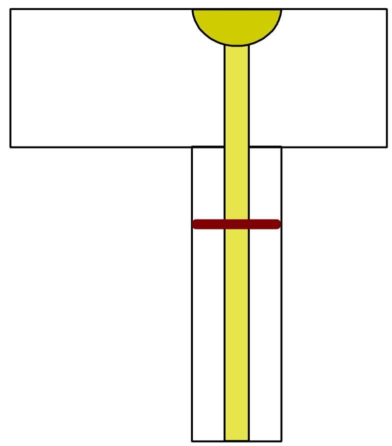
Special Considerations for Spoke Couplers

- Small apertures of spoke resonators require coupler attachment to cavity volume
- Magnetic loop vs. coaxial antenna coupling
- Thermal loads of the coupler influence cavity
- Thermal radiation from coupler into cavity needs consideration
- Cavity-Coupler interface might influence frequency

Geometry Choice

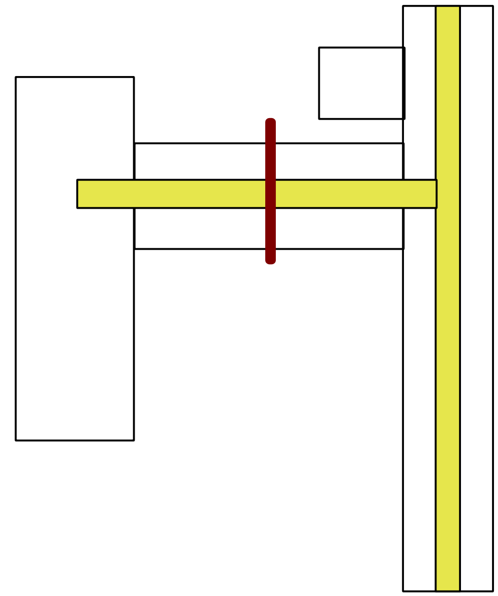


Tristan-type
- Free orientation
- Proven w/ beam
  at 225 kW
- Good vacuum@ window
- Small footprint
- Low cost



KEK-type
- Proven w/ beam at 380 kW
- Small footprint

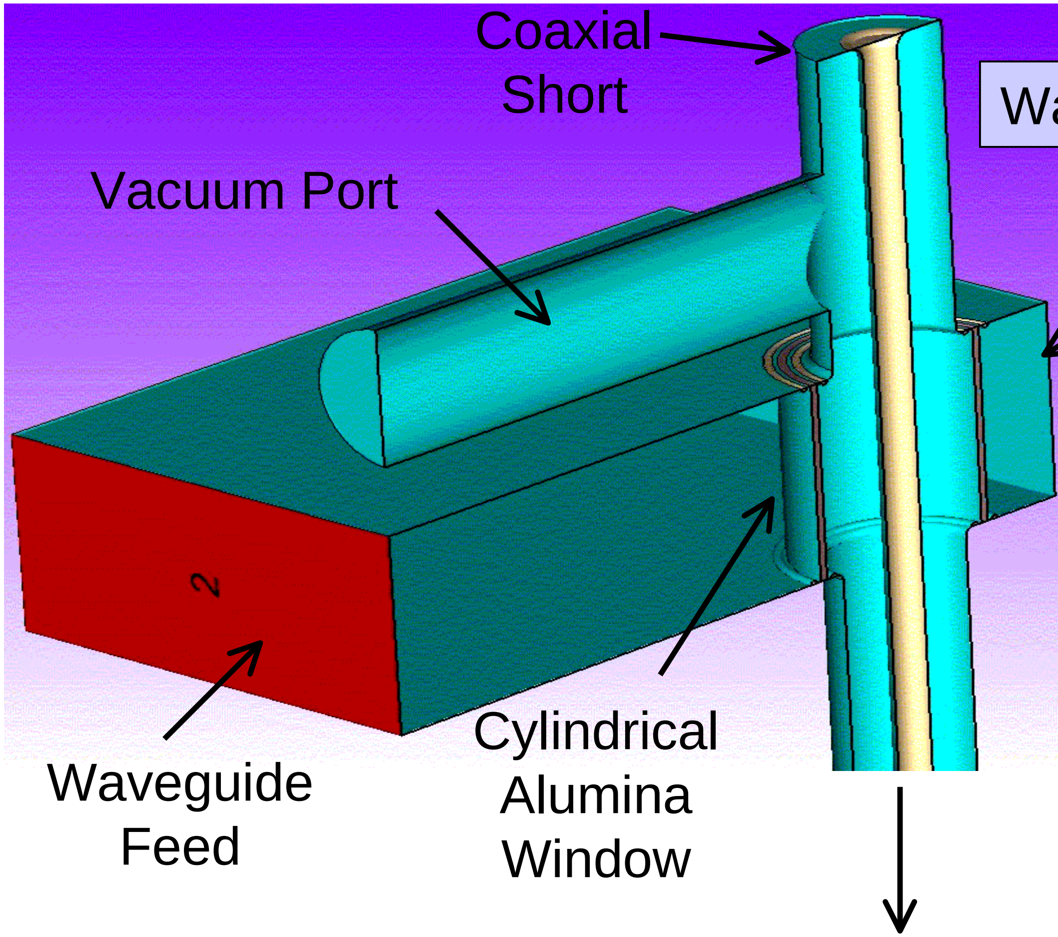
- Up or down orientation only
- No straight forward addition
  of additional pump port



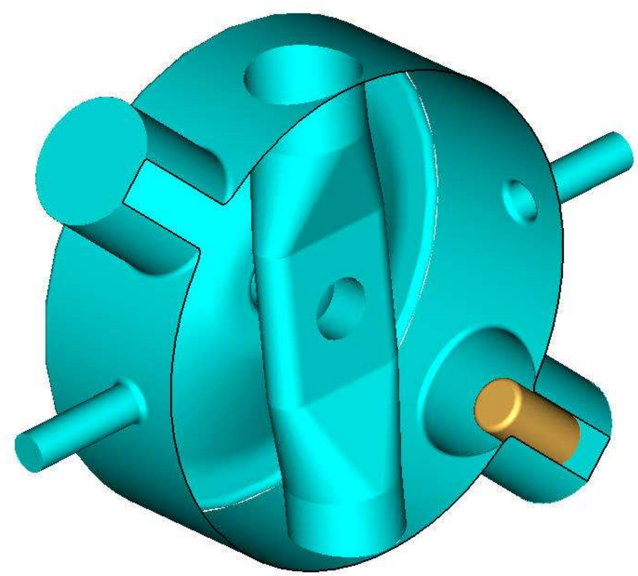
APT-type
- Free orientation
- Proven w/o beam at 1 MW
- Good vacuum @ window
- Local experience

- Big footprint
- High cost

Geometry Features



Warm part of the coupler



Multipacting Consideration for Coaxial Line Size

1. Criterium: Multipacting vs. Beam Power:

Single Point MP levels compared between CERN and derived ADTF scenarios

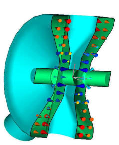
Order	CERN	ED&D-103	ED&D-100	APT-Geo
	352 MHz 75 Ω	350 MHz 75 Ω	350 MHz 75 Ω	350 MHz 50 Ω
7	48 kW	47 kW	42 kW	28 kW
6	52 kW	51 kW	45 kW	30 kW
5	88 kW	86 kW	76 kW	51 kW
4	176 kW	172 kW	153 kW	102 kW
3	234 kW	229 kW	204 kW	136 kW
2	448 kW	438 kW	389 kW	259 kW
1	640 kW	626 kW	556 kW	371 kW

Average Input Power Levels for the Spoke Resonators (ϕ=–30^o)

	13.3 mA	100 mA
β=0.175	6 kW	43 kW
β=0.34	19.5 kW	144 kW
for E_0T = 5 MV/m		

	13.3 mA	100 mA
β=0.175	8.5 kW	63.6 kW
β=0.34	28.2 kW	211.8 kW
for E_0T = 7.5 MV/m		

2. Cavity Size: The β=0.175 cavity is limited to coax sizes around approximately 100 mm



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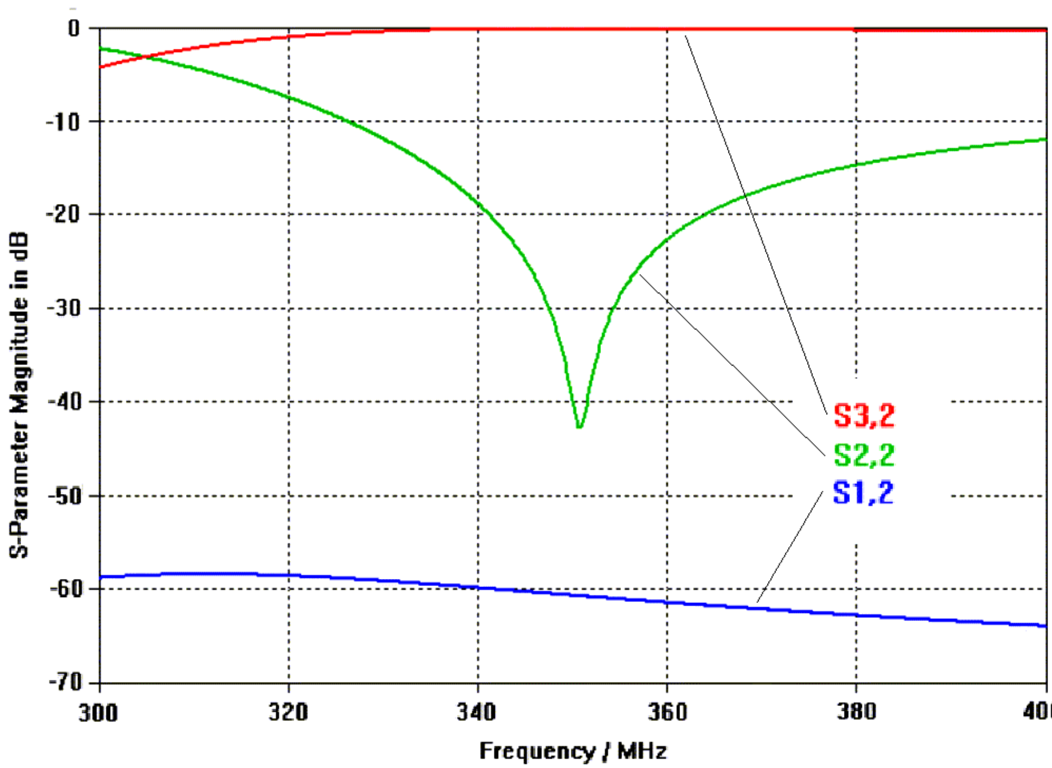
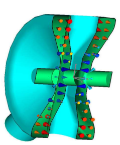
Geometry Parameters and RF Performance

Coax diameter	103 mm
Coax impedance	75 Ω
Waveguide	WR3200
Window-type	cylindrical
Window-material	95% pure ($\varepsilon = 9.1$, $\tan\delta = 0.0027$)
Window OD	139.7 mm
Thickness	4.8 mm
Transition	½-height waveguide to $\lambda/4$ stub

Coax short	305.5 mm to window center
Waveguide short	130 mm to window center
Vacuum port	140 mm to waveguide top
Coax-length	1196.7 mm from short to tip
Pump flange	450 mm to coax center
Orientation	45 degrees from spoke
F_{match}	350.1 MHz
S11	-45 dB
bandwidth	± 11 (3) MHz at -20 (30) dB

S-parameters





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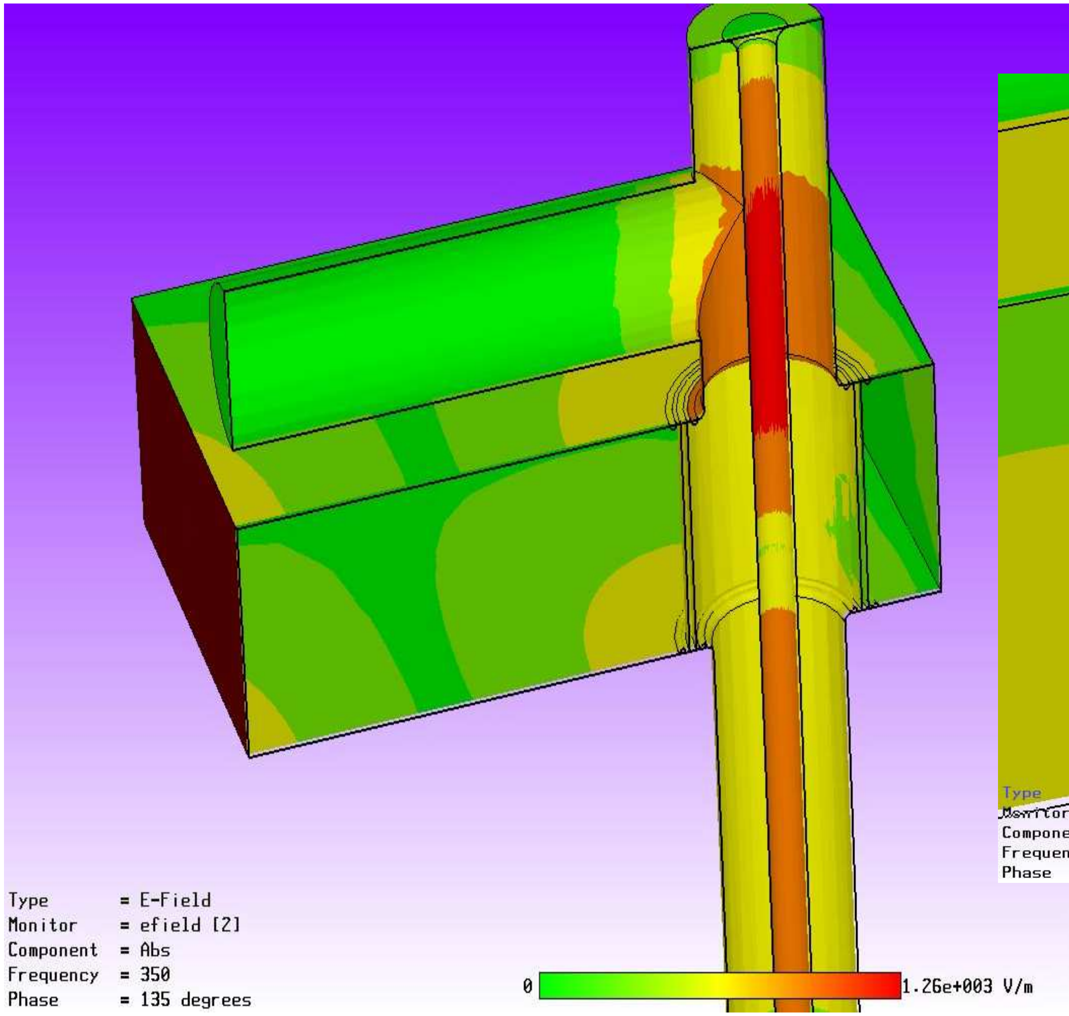
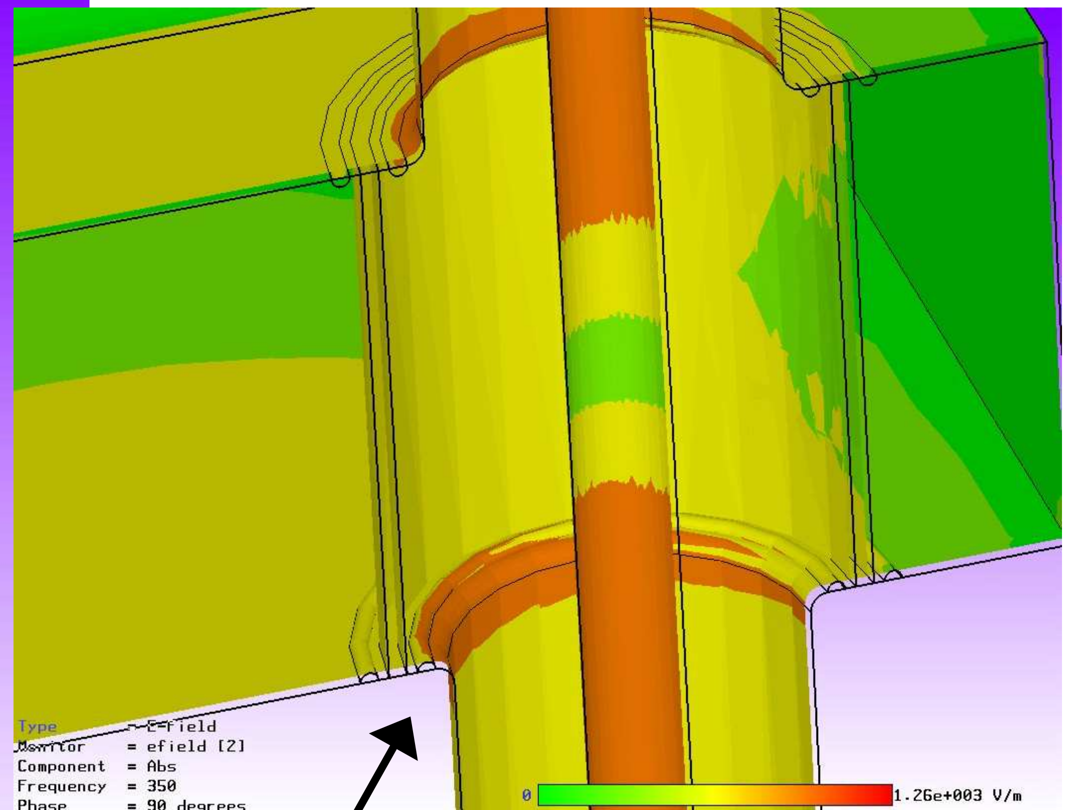
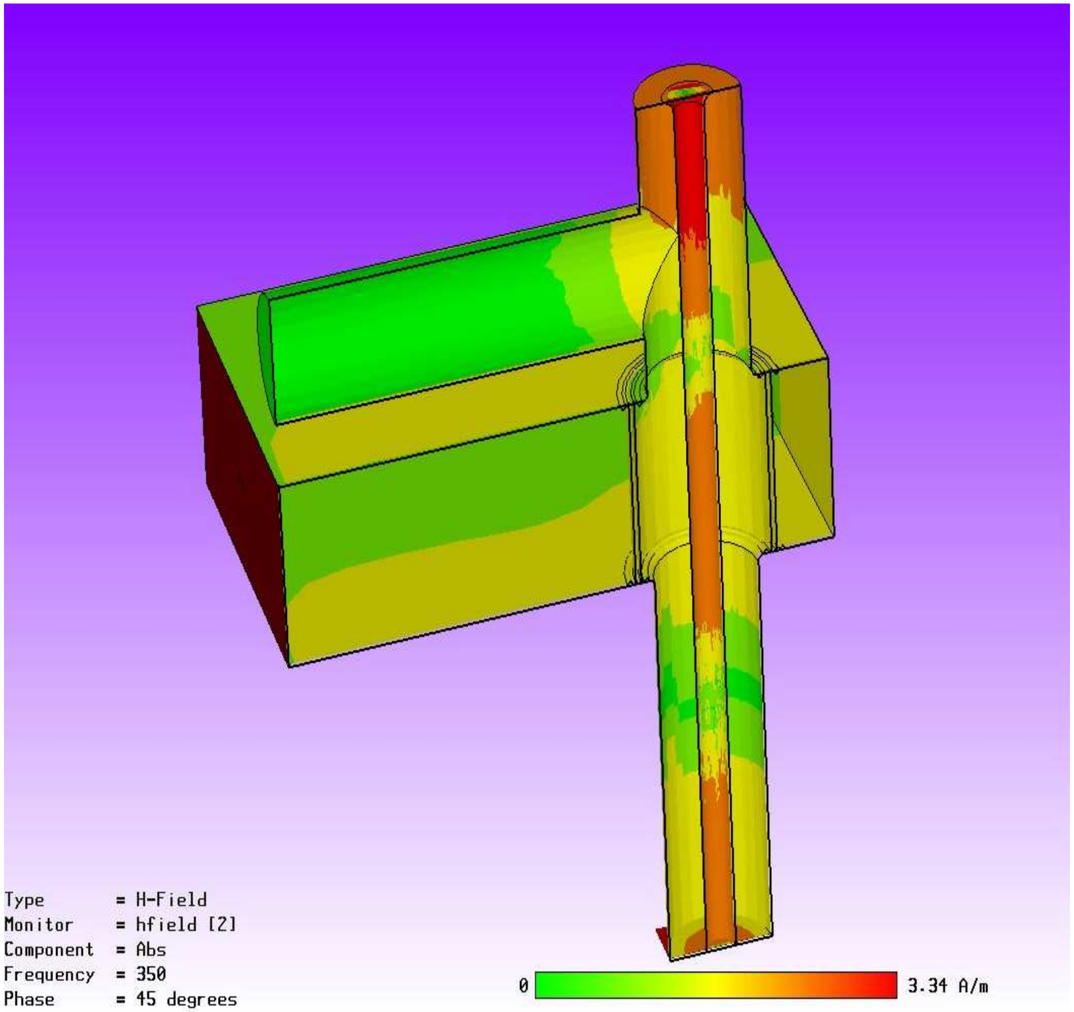
Electric Field

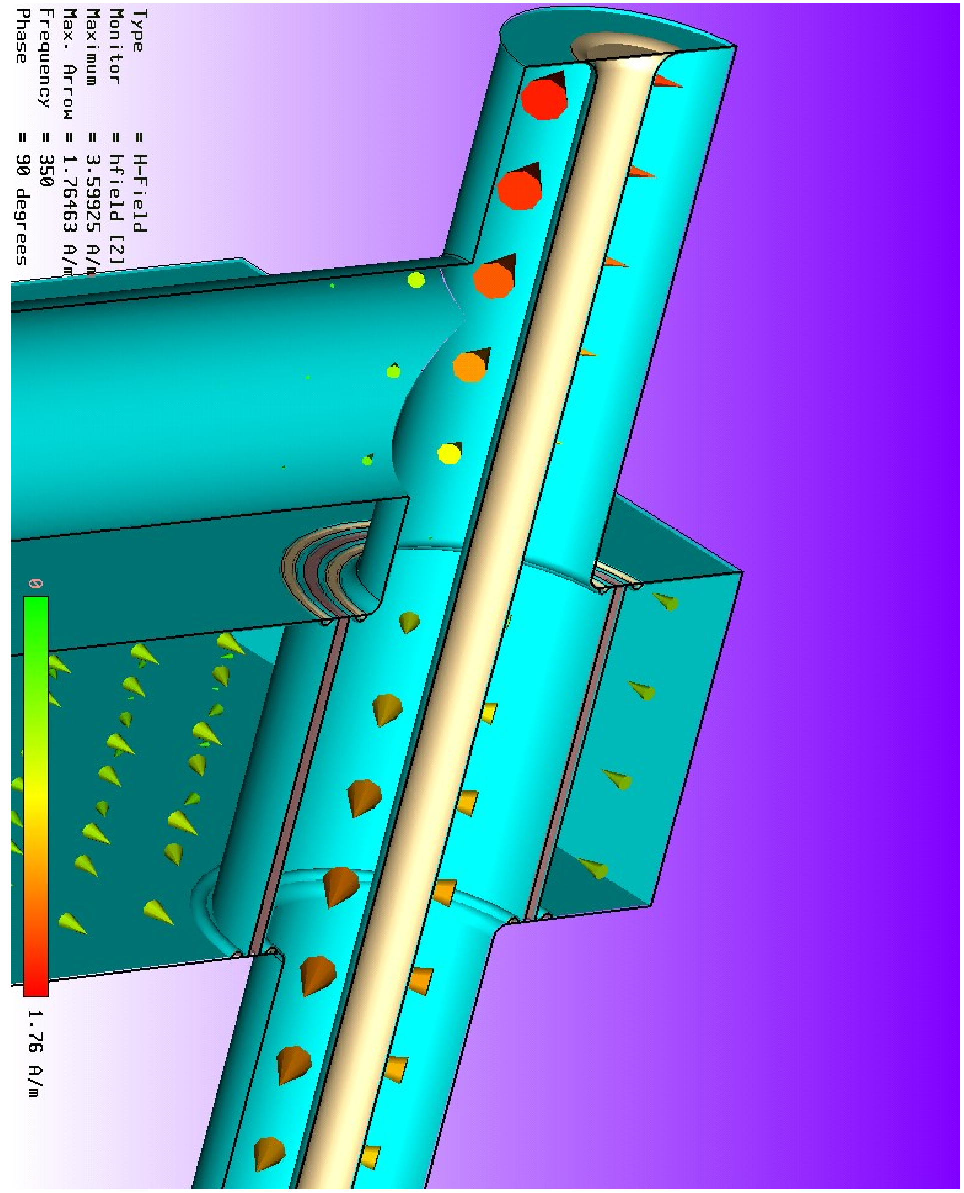




Braze Protection

Magnetic Field





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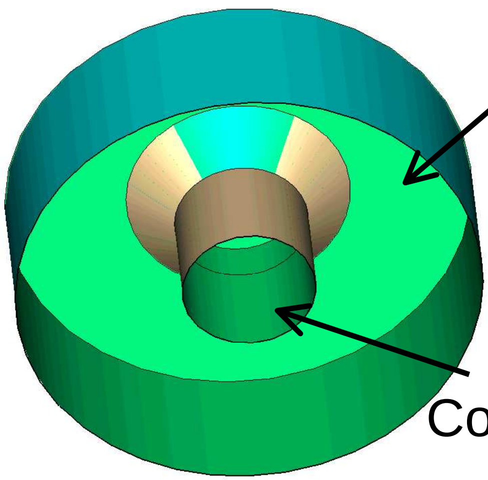
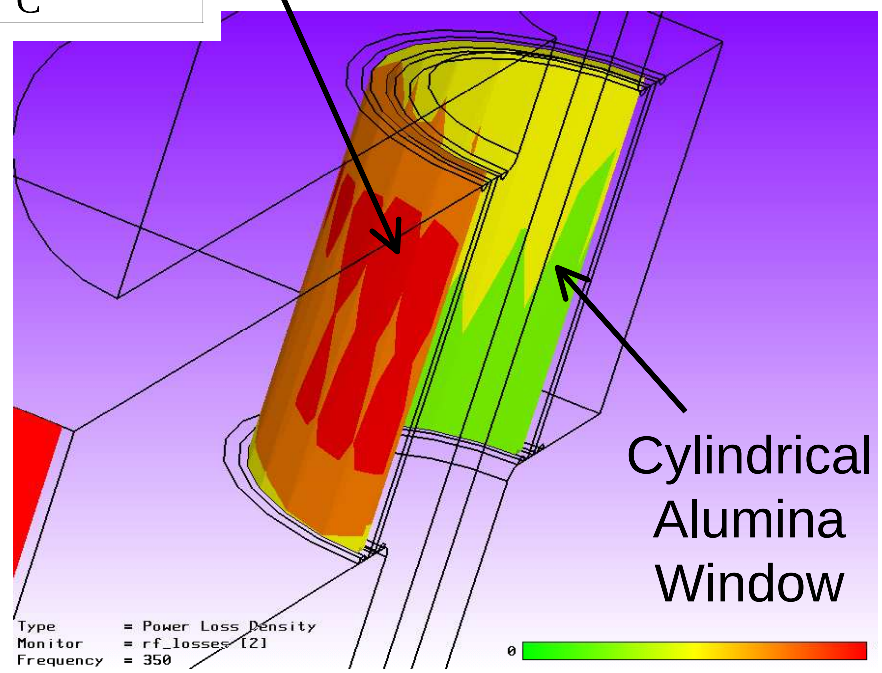
Power Coupler: Thermal/Structural Evaluation

Beam Current Transmitted Power	13.3 mA 8.5 kW	20 mA 12.8 kW	100 mA 63.6 kW
Coax-center, Straight Coax	3.6 W	5.135 W	26.90 W
Coax-center, Actual Coupler	3.94 W	5.93 W	29.48 W
Coax Short	113 mW	170 mW	843 mW
Waveguide Short	116 mW	174 mW	865 mW
Window Ceramic	6.6 W	9.9 W	49.4 W
Peak Loss in Window [W/cm^3]	0.04	0.06	0.27
Peak Temperature on Window	< 47^o C		
dT$_{max}$ across Window	2^o - 22^o C		

Goals:
1. Input for thermal
2. Critical spots
3. Cooling needs

Inner conductor cooling: GHe
Window cooling: dry air





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Summary

- The basic properties of a high power coupler have been selected:
  - coaxial coupler with a $\lambda/4$ wg to coax transition.
  - electric coupling directly to cavity body.
  - coupling scheme has been verified in the lab.
  - coaxial dimensions selected to avoid mulitpacting at operation power level.
- Based on this a RF design has been done with established 3D simulation codes.
- The basic foot print of the coupler has been established.
- Some sensitivites for fabrication are being established.
- The cavity coupler interaction has been studied.
- The basic RF losses have been determined as input for a thermal and stress analysis.
- Further optimization will not change the essence of the results obtained to date.

Discussion on "Design of a Power Coupler for the AAA Spoke Resonators" by Frank Krawczyk

The discussion mainly focused on the port size issue. Krawczyk answered on the proposed scenario of having to transmit a maximum of 35 kW. He would prefer to go to a smaller coupler port to mitigate some of the problems introduced by the large port size of the present design. Tajima added that for cleaning and processing the large port size is still desirable and that the main problems might be resolved if the RF-joint is moved further away from the cavity instead. Rusnak added a proposal to maintain the coupler as is and neck down the port size close to the cavity, e.g. by a taper. Tapers have been shown in some cases to add to the likelihood of multipacting. This could be avoided if the taper is in a fully warm or cold region. This would keep condensed water vapor away from its surface. Water vapor is the main source of increased secondary emission in coupler lines.

In a final point Krawczyk detailed the frequency change due to the coupler position. Changing the coupler from 13 to 20 mA operation changes the cavity frequency by 200 kHz. This can easily be compensated by the slow tuner. A change to 100 mA requires a 1 MHz change, which uses 50% of the tuning margin allowed from mechanical considerations.

Miscellaneous Issues

Frank Krawczyk: "*Issues Related to the Modeling of Multipacting for Spoke Resonators*"
(Abstract | Viewgraphs | Discussion)

Terry Grimm: "*Higher Order Modes in Spokes - Are they a Problem?*"
(Abstract | Viewgraphs | Discussion)

Issues Related to the Modeling of Multipacting for Spoke Resonators

Frank Krawczyk, LANL

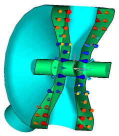
The evaluation of multipacting effects has become a common part of the design procedure for elliptical cavities in recent years. This is due to the increased quality and availability of simulation codes for 2D applications. The more complex spoke resonators require full 3D simulations. For these applications software availability is limited. The presentation will give a short overview on the simulation procedure that is common to most multipacting simulation software. An application of MultP to an ANL spoke resonator will be used to trigger a discussion on simulations needed and on potential locations in spoke resonators where multipacting might be happening more likely.

Multipacting Simulations for Spoke Resonators

Frank Krawczyk
LANL

Workshop on the Advanced Design of Spoke Resonators

Los Alamos, NM, USA
October 7 and 8, 2002



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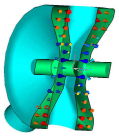
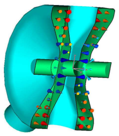
Introduction

- Motivation
- Simulations Approach
- Method Overview
- Existing simulation result
- Outlook



Motivation

- Spoke resonators show multipacting
- The effect is no show stopper but annoying for operation/start-up
- Established multipacting simulation software exists mostly in 2D
- 3D simulators or coming up (XING, Cornell for wave-guides, MULTP for general geometries)
- We need simulations to understand locations of multipacting (flat part of spoke/outside wall 90^o from spoke base/ other ??)
- Can we get rid of multipacting by reshaping the problem spots?



Simulations Approach to Multipacting

Common approach by all simulation software:

- Geometry description
- EM-field description (quality of surface field)
- Surface property description (SEY)(accurate knowledge)
- Particle description: location, energy, (re-)emission
- Scanning of parameter space (field levels, particle energies, rf -phases, emission angles)
- Statistics to identify recurrence patterns

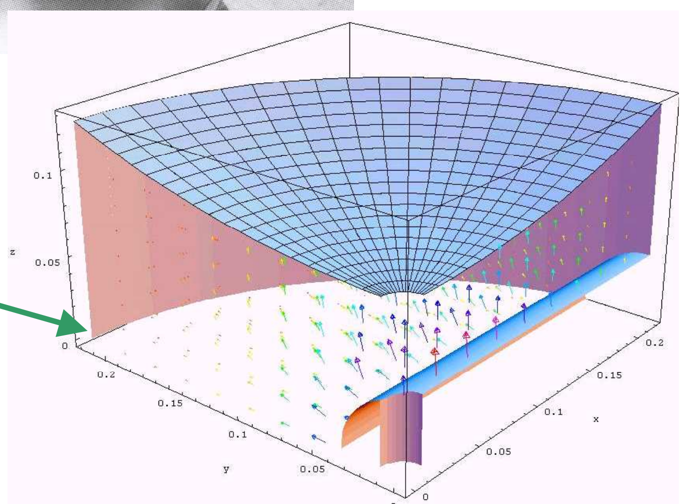
Method Overview

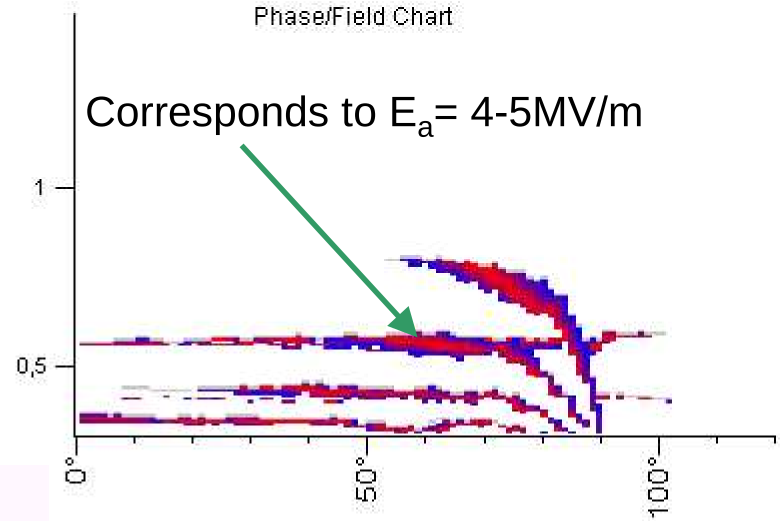
Geometry + EM Field Description

Introduction of particles and material properties into original or processed fields:
Scan parameter space (particle and field related) for many particles

Statistics to identify recurrence, multiplication

MULTP Results for ANL Spoke





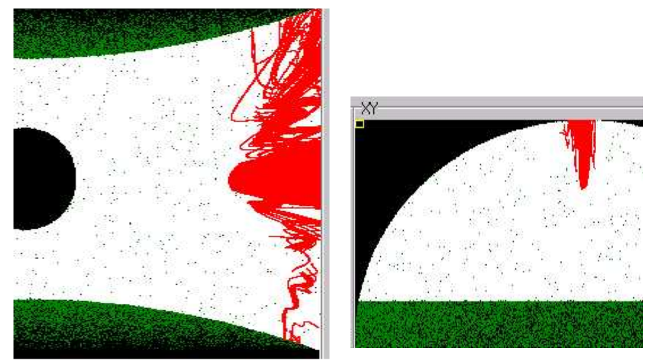
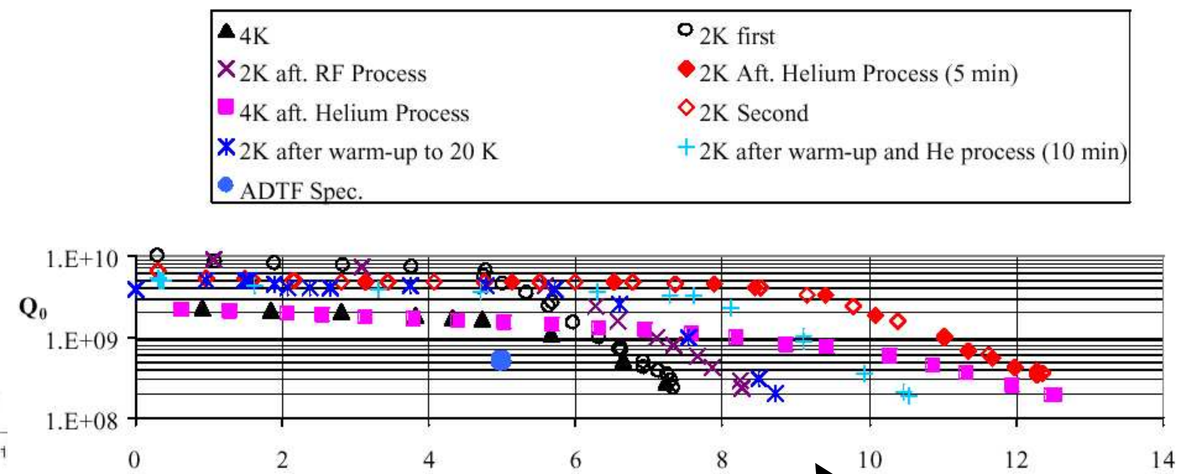


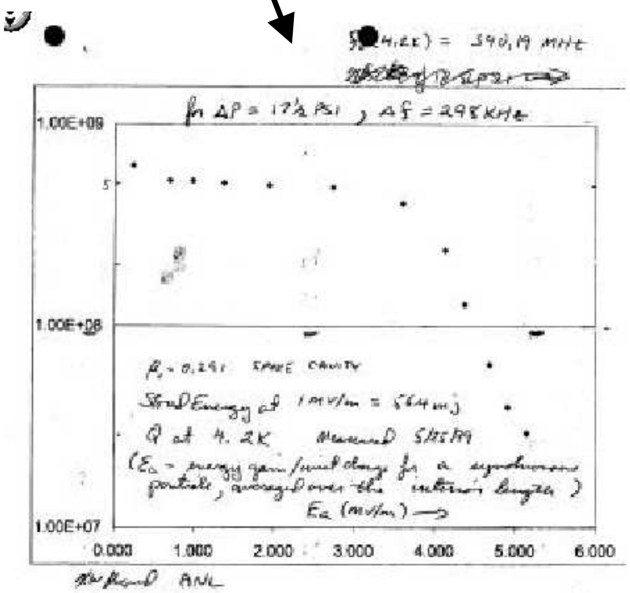
Fig.12a. The electron trajectories of the resonant multipaction.

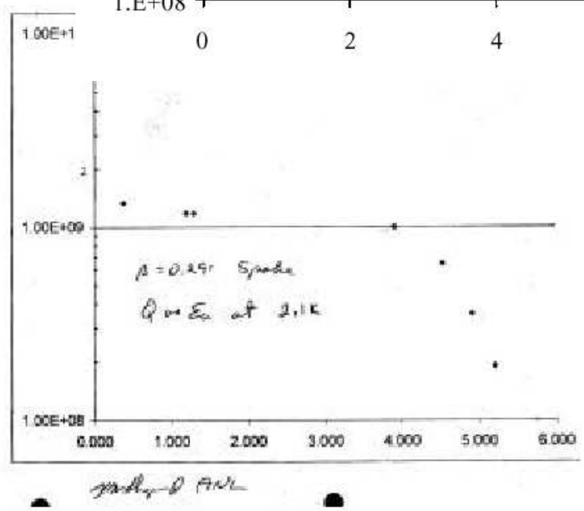
MULTP Results for ANL Spoke

ANL beta=0.3 spoke cavity Q vs. Eacc (3/29-4/4, 2001)



Original Measurement





Measurement with improved surface

Outlook

Things needed to improve the understanding:

- Evaluate existing 3D software and compare with measurements
- Identify multipacting locations
- Evaluate geometry modifications

Discussion on "Issues Related to the Modeling of Multipacting for Spoke Resonators" by Frank Krawczyk

The first discussion elaborated on a simulation result that Krawczyk presented for the ANL β=0.4 spoke resonator. The original measurement for the Q vs. E showed a drop in Q around 4 MV/m. This coincides with a predicted multipacting level from the MULTP code. It was remarked that the fact that the Q-drop was removed at LANL by BCP and HPR could also mean that the drop was due to field emission. Shepard added that sometimes the signature of events does not clearly distinguish between multipacting and field emission.

Shepard then listed his general experience with drift space and spoke structures. All these structures show multipacting at very low field levels. He believes that this is 2-point multipacting across the acceleration gaps. This activity can be removed by processing. The processing time varied from fractions of an hour to many hours. A conditioned, cold structure maintained this conditioning. This type of multipacting is not an issue in these structures. Also commissioning on a beam line can handle the requirement of this type of processing, as has been demonstrated for ATLAS. Delayen added that this confirms their experience that commissioning requires one person for one day per structure.

Facco added that they could demonstrate that multipacting in their quarterwave structures happened at a different location than the gaps. They localized it half-way between the gap and the shorting plate. They found the location by disrupting multipacting trajectories by an external small magnet they moved along the outside of the cavity until the multipacting stopped. Facco further provided information about their processing. They do their processing at room temperature. The conditioning seemed to be maintained. The advantage of room temperature processing is the reduced consumption of liquid helium and the additional outgassing of the RF-surfaces during the conditioning.

Shepard continued the listing of his experience by naming high level multipacting barriers (starting at 3 - 5 MV/m) as the real concern in these structures. Not all structures do exhibit this behavior, but when it appears it is much more troublesome. Processing these levels is much harder, as at these levels thermal instabilities at the impact site might be triggered.

He is interested in working with LANL on taking a closer look at the 4 MV/m behavior of the ANL β=0.4 spoke resonator by simulations and measurements. He proposed to do "2nd sound" diagnostics to identify multipacting and compare the results with the simulations to benchmark the codes.

Krawczyk re-emphasized that there is potential, but no clear evidence of multipacting at 4 MV/m for the tested ANL structure. He thinks this event might be a good candidate to study and benchmark simulations.

Next the difference in processing between the ANL and LANL spoke resonators tested at LANL was discussed. The geometric difference is that the LANL cavity (with a long processing time) had flat surfaces in the gaps, while the ANL cavities (with a short processing times) did not have these flat surfaces. Shepard added that flat surfaces and large areas of cylindrical symmetry seem to be always worse. Still there are not sufficient data to confirm the relationship between the processing time and geometric features.

Kelly reported that during the tests of the ANL spoke resonators soft high level barrier appeared that were simply processed within a short time. The 4 MV/m barrier presented in the presentation might have been one of them. Krawczyk admitted that he does not know enough about the MULTP code to know if the simulation results include any qualification about the severity of a barrier.

HOMs in Spokes - Are They a Problem?

T. Grimm, Michigan State University

Higher-order mode (HOM) damping will be required in many accelerators, regardless of the cavity types, to eliminate beam instabilities. Multi-bunch instabilities (transverse, and longitudinal for $v/c<1$) become an issue as beam intensity increases. Superconducting elliptical cavities have demonstrated many solutions to effectively damp HOMs and thus control instabilities. A comparison of spoke and elliptical cavity HOM issues is presented along with examples from pulsed and cw machines (SNS and RIA).

HOMs in Spokes
Are They a Problem?

Spoke Workshop
October 8, 2002

Terry L. Grimm
National Superconducting Cyclotron Laboratory
Michigan State University

- **Beam loading of HOMs**
- **HOMs in spokes and elliptical cavities**
- **Longitudinal & transverse stability analysis**
- **HOM damping requirements**
- **HOM damping techniques**

NSCL

Beam Loading

- **Treat bunch as a point charge, q**
- **Single point charge induces a voltage**

$$V_q = \mp \frac{\omega_n R}{2Q} |q| \exp(i\omega_n t) \exp(-\frac{t}{T_d})$$

$$\frac{R}{Q} = \frac{\left| \int E_z(r,z) \exp(i\omega z / v) dz \right|^2}{\omega U}$$

- **Voltages induced in all higher order modes at their respective frequency**
- **Later bunches add via superposition, and thus see different voltages until equilibrium is reached (ie. cw beam)**
- **Worst case, on resonance with $T_b << T_d$**

$$V_b = V_q \frac{T_d}{T_b}$$

$$= \frac{R}{Q} Q_L I_o$$

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HOMs

- **Elliptical Cavities**
  - **Axisymmetric, single/hollow conductor**
  - **Cylindrical waveguide modes**
    - **TE and TM modes**
  - **$TM_{010,\pi}$ for acceleration**

- **Spoke Cavities**
  - **Two conductor structure**
    - **Coaxial TEM modes**
    - **Coaxial TE and TM modes**
    - **Cylindrical waveguide modes**
  - **$\lambda/2$ (1^{st} TEM mode) for acceleration**

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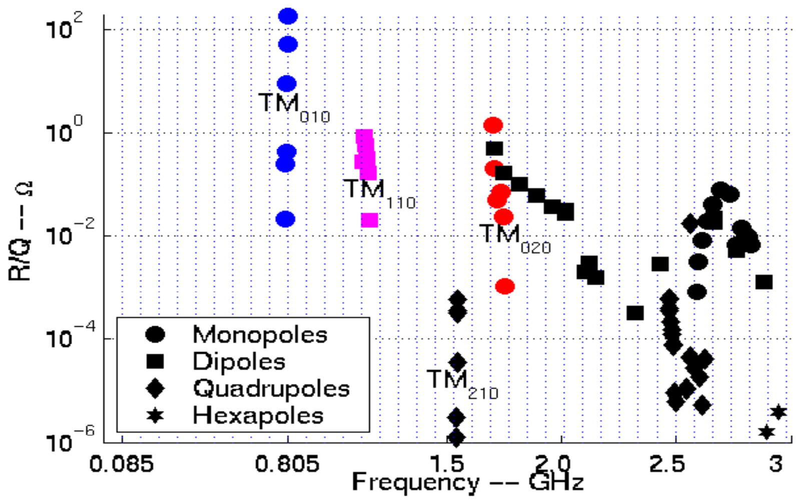
Shunt Impedance

- **Elliptical cavities**

  Sacrifice R/Q for large aperture
  and tapered walls
  All HOMs couple to the beam tubes

RIA 805 MHz β_g=0.47 six-cell (7.7 cm aperture)



- **Spoke cavities**

  Higher shunt impedance for
  accelerating mode and HOMs
  Smaller aperture
  More difficult processing

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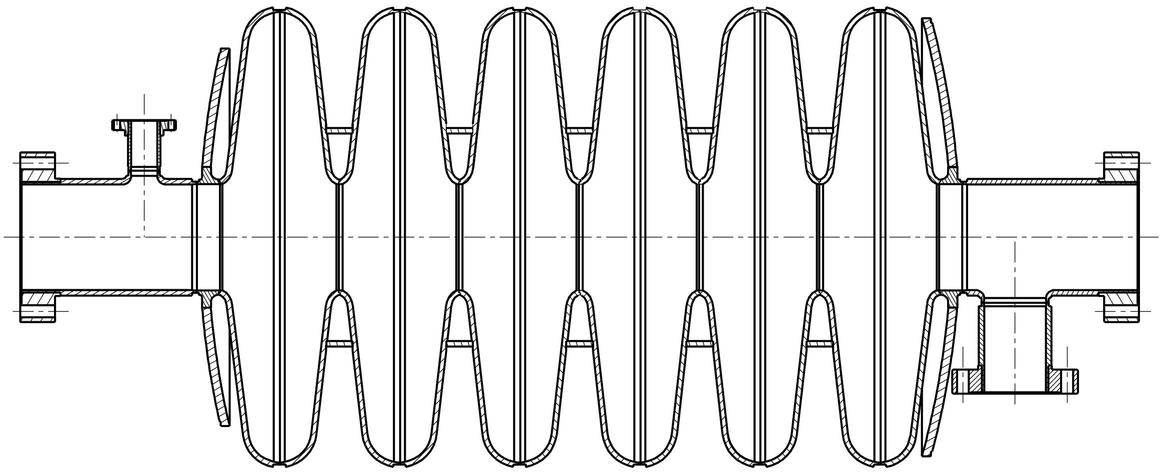
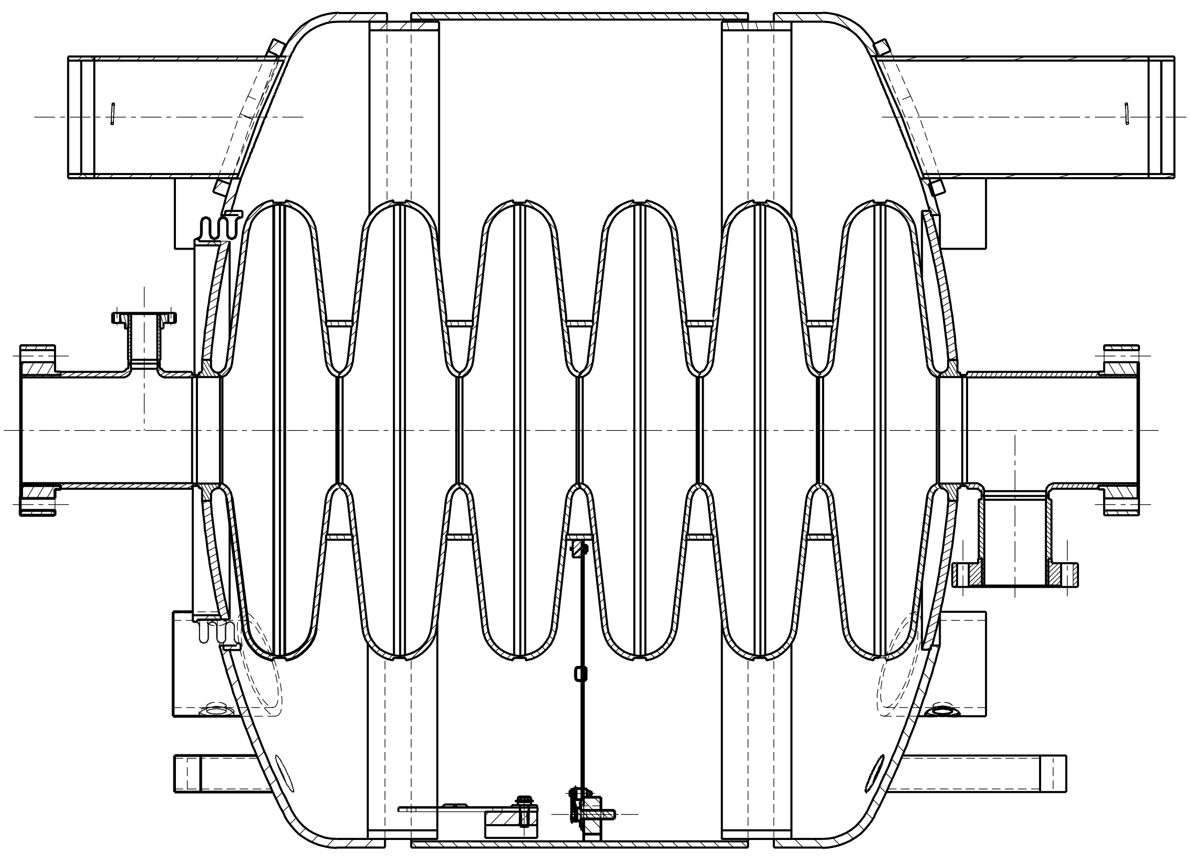
β=0.47 Final 6-Cell Prototype





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Instability Analysis

- **Multi-bunch, single pass**

  $\beta<1$ can have longitudinal or transverse instability

- **Simulation with point charges**

  HOM frequency spread due to fabrication

  SNS 0.02 % (standard deviation)

  Focussing lattice

  Cavity and magnet misalignment

- **For a given Q_L track**

  Longitudinal voltage for each bunch

  Transverse kick generated for each bunch

  Track through lattice

- **Determine acceptable Q_L**

  Emittance growth (long. and trans.)

  Halo formation

  Excessive cavity voltage

  Excessive cryogenic power

NSCL

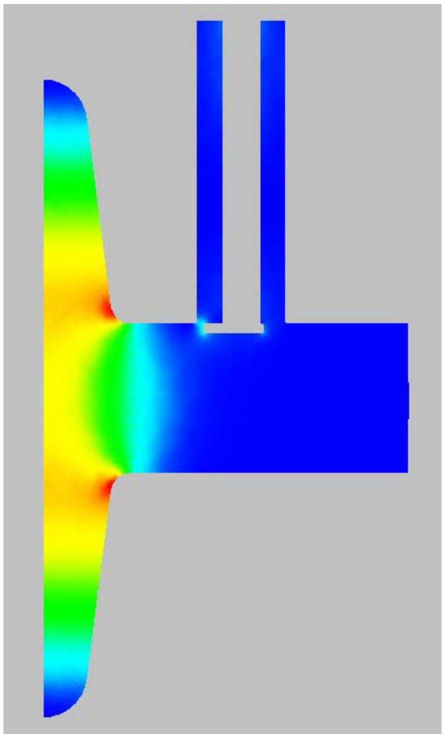
Instability Analysis - Examples

- **SNS (Sundelin et al, PAC01)**
  52 mA, 6% duty cycle

  β=0.61 & 0.81 six-cell 805 MHz
  HOM dampers must limit $Q_L<10^8$
  Cavity to cavity frequency variation
  Passband modes Q_L are as predicted

- **RIA (Grimm et al, EPAC02)**
  0.38 mA, cw

  β=0.47 six-cell 805 MHz
  Power coupler and pickup adequately damp HOMs without need for additional HOM couplers



Damping Techniques

- **Increase damping of HOM (lower $Q_L = \omega U/Ptot$)**
  - Ptot=Po+Pcoupler+Ploss
  - Couple power out of cryogenics
    - Coaxial antenna with high pass filter
    - Rectangular waveguide
    - Ferrite load on beam pipe wall
- **Elliptical cavities**
  - HOMs field in beam pipe
    - Easy access, outside He vessel
  - Above cutoff propagate in pipe (low Q_L)
    - 7.7 cm aperture, high pass filter
    - TE11- 2.28 GHz, TM01- 2.97 GHz
- **Spoke cavities**
  - Power and transmission coupler
  - Additional couplers with filters
    - Lower Q_L
    - Trapped modes
  - Beam pipe has very high cutoff frequency

NSCL

HOM Measurements

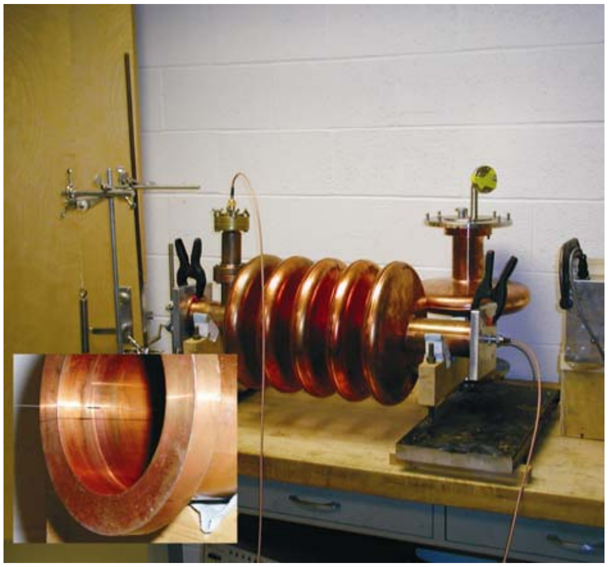


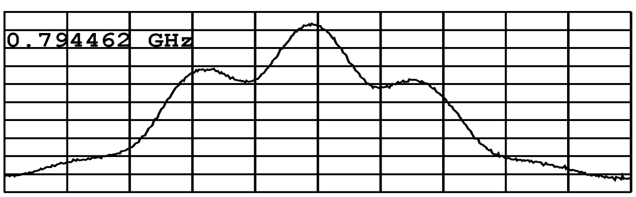
Table 1: Input power coupler Qext for single cell HOMs with penetration into beam tube of 5mm.

f	Qext	Type	*f*	Qext	Type
0.805[a]	2.17×10^{6}	TM010	**2.041**	1.11×10^{4}	TM120
1.154[b]	9.58×10^{5}	TM110	**2.270**	6.40×10^{11}	TM410
1.547	1.58×10^{8}	TM210	**2.476**	3.10×10^{5}	TM220
1.725[c]	3.41×10^{5}	TM020	**2.591**	2.43×10^{4}	TE211
1.897	6.30×10^{3}	TE111	**2.627**	5.61×10^{3}	TM030
1.939	1.93×10^{4}	TM310	**2.720**	3.90×10^{2}	TM121

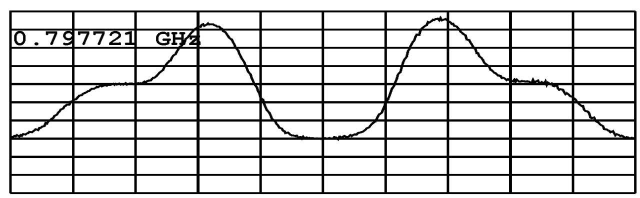
Qext results confirmed experimentally:
(a) 2.82×10^{6} *(b)* 1.53×10^{6} *(c)* 4.42×10^{5}

$| E_z(r,z) |^2 \; TM_{010}$ 5 CELL measurements

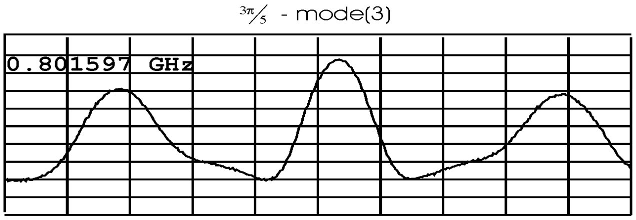
$\pi/5$ - mode (1)



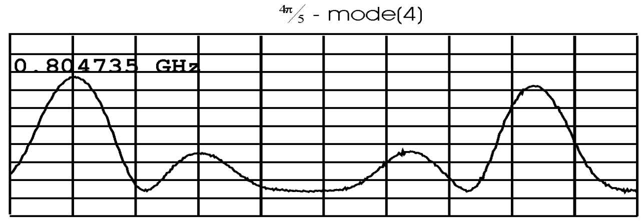
$2\pi/5$ - mode(2)



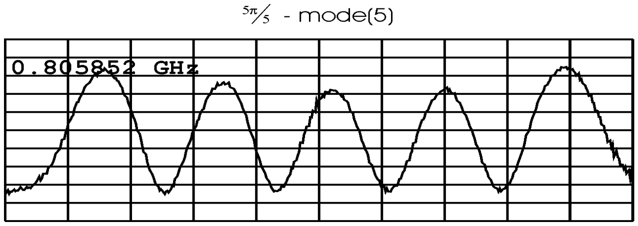
$3\pi/5$ - mode(3)



$4\pi/5$ - mode(4)



$5\pi/5$ - mode(5)



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Conclusion -- HOMs

- HOM damping is required for many accelerators

- Elliptical cavities

  Demonstrated solutions
  Power & HOM couplers on beam pipe
  outside Helium vessel

- Spoke cavities (single and multi-spoke)

  Implement same techniques as elliptical
  Location of couplers may be problematic
  Large HOM frequency range to damp due to
  small beam pipe

Discussion on "HOMs in Spokes - Are They a Problem?" by Terry Grimm

Grimm explained that the explicit β-variation has not been taken into account in their evaluation of the HOM mode Q-values, the worst case has been selected instead.

Shepard shared their experience that small ports to remove HOM-power from the cavity are not a problem for these resonators. There is no need to locate them on the very small beam pipes that have a very high cut-off frequency, as Grimm had suggested. There is a further advantage of locating the HOM ports (if needed) onto the cavity body. Both, electric and magnetic fields will couple to simple coaxial antennas and trapped modes should be less of an issue.

On the question of the agreement between simulations and measurements Grimm presented data for a RIA β=0.47 elliptical cavity. HOM frequencies agreed within less than 1%, Q-values agreed within 20%, which is reasonable. He confirmed that the measurements were done using an antenna that was a reasonable mock-up of the actual power coupler. The result of the simulations for RIA did not show any dangerous modes. The evaluation of the danger of the modes used the actual RIA lattice and beam structure. A reasonable spread of HOM frequencies along the accelerator has been applied.

In a next topic some simulation issues have been discussed. Delayen cautioned against drawing conclusions from simulated field-flatness data of HOMs for structures with low cell-to-cell coupling. The related external Q-values can be off by up to 3 orders of magnitude from the measured values. This is related to the fact that structures are only tuned for the fundamental accelerating mode. The effect of the tuning onto any other modes is totally arbitrary and results in unpredictable field levels for each mode at the position of the HOM coupler. This provides another advantage for spoke resonators, as for structures with strong cell-to-cell coupling the behavior of HOMs is more predictable.

The final discussion point was related the differences between the significance of HOMs for SNS and RIA. The 4K operation of spoke resonators lowers the Q_x of HOMs and thus makes them less dangerous. The cw-operation of RIA also significantly reduces the harmonics excited by the beam. This reduces the likelihood of exciting HOMs.

Cryomodules

Joel Fuerst: "*Spoke Resonator Cryomodule Designs*"
(Abstract | Viewgraphs | Discussion)
Jean-Luc Biarrotte: "*XADS/Eurisol Cryomodule - Options for a Highly Reliable Spoke Linac*"
(Abstract | Viewgraphs | Discussion)
Pat Kelley: "*ADTF Spoke Cavity Cryomodule Concept*"
(Abstract | Viewgraphs | Discussion)

RIA

J. Fuerst, Argonne National Laboratory

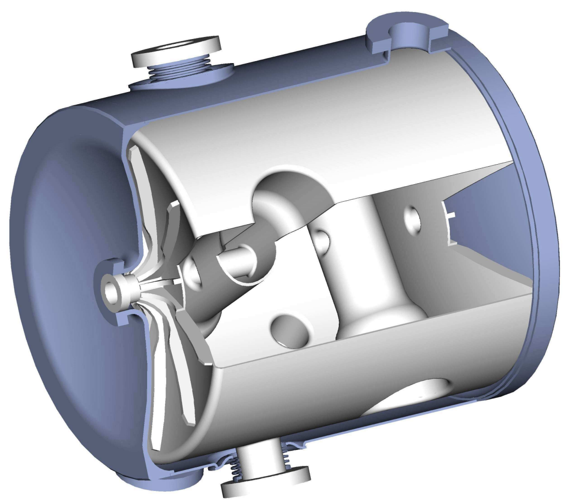
Designs for the Rare Isotope Accelerator (RIA) driver linac include anywhere from 50 to 170 superconducting spoke resonators. We present several cryomodule design options for these resonators that explore both top-loading and end-loading geometries. The resonator helium vessel design uses 316L stainless steel, brazed Nb to SS transitions and Conflat seals. Fundamental module design choices such as separate vs. common beam and insulating vacuum spaces are driven by the clean fabrication techniques required for optimum cavity performance.

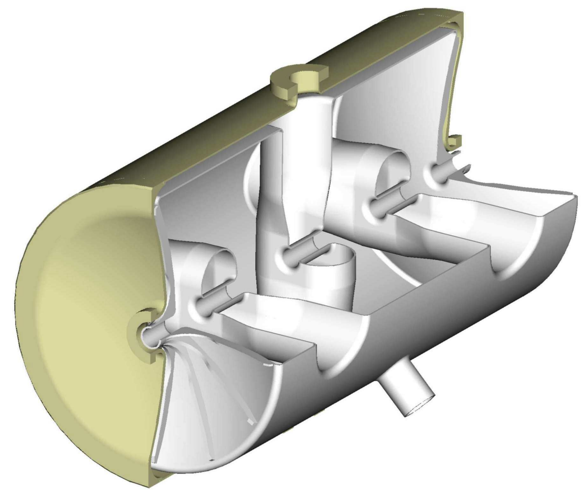
RIA Spoke Resonator Cryomodule Designs

Joel Fuerst

Argonne National Laboratory

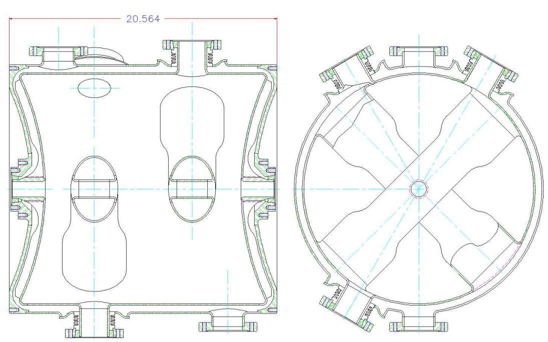
RIA Spoke Resonator Geometries

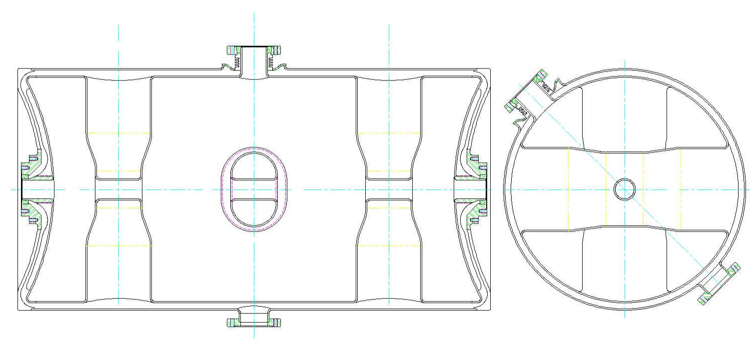




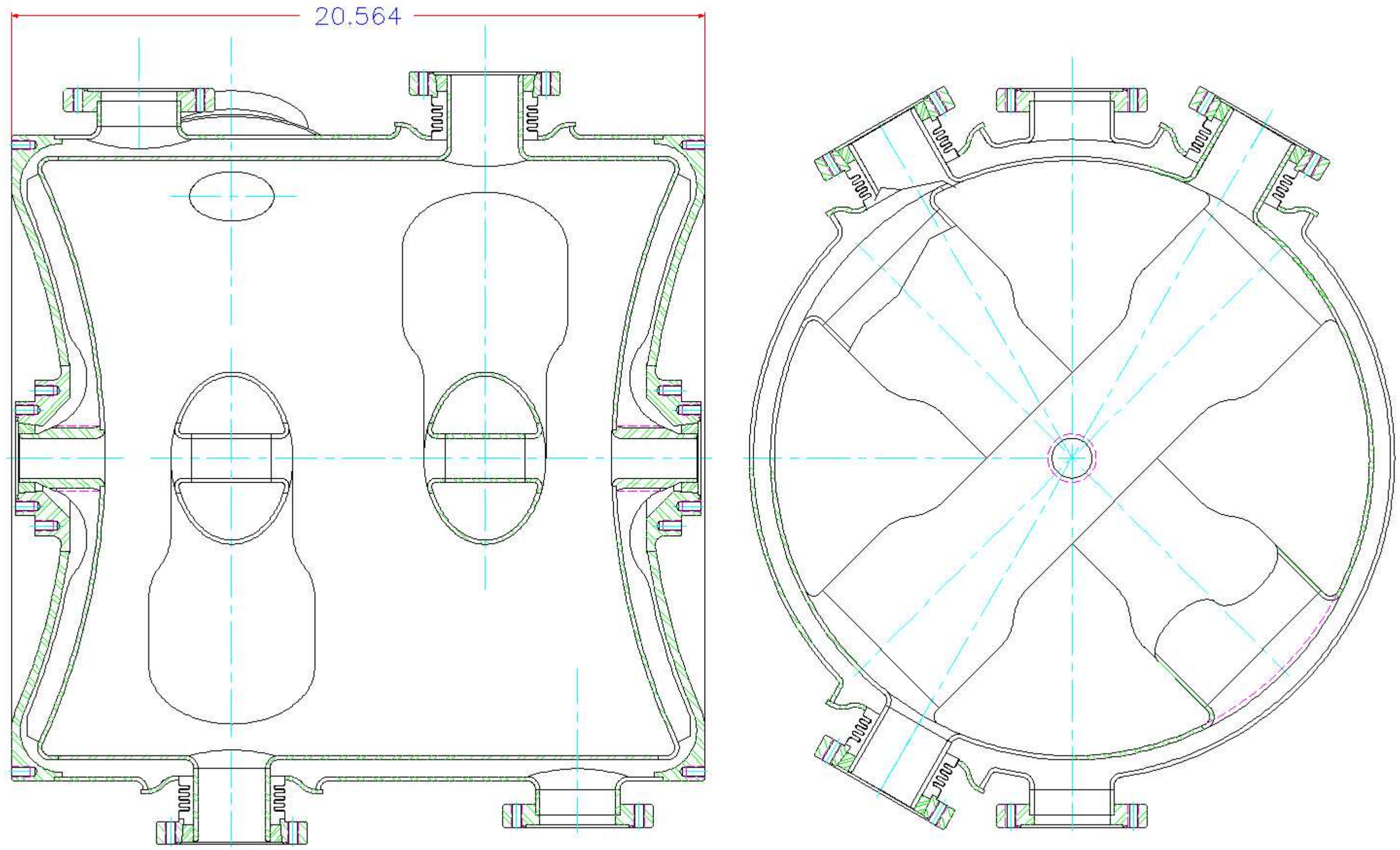
~63 3-gap cavities required for std. driver design (9 modules)

170 4-gap cavities required for alternative design (48 modules)





316L SS LHe vessel



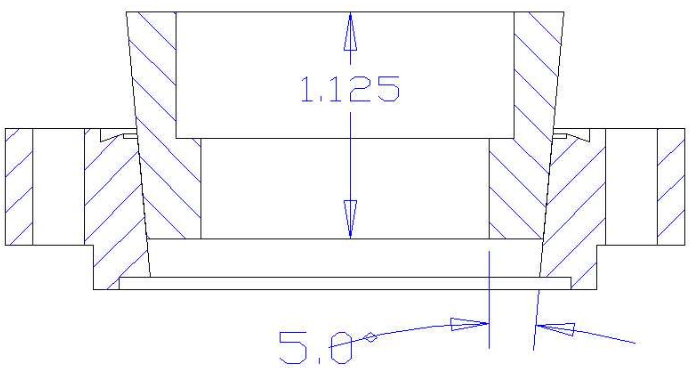
- SS shell with CF flanges using commercial Cu gaskets
- straightforward TIG welded shell

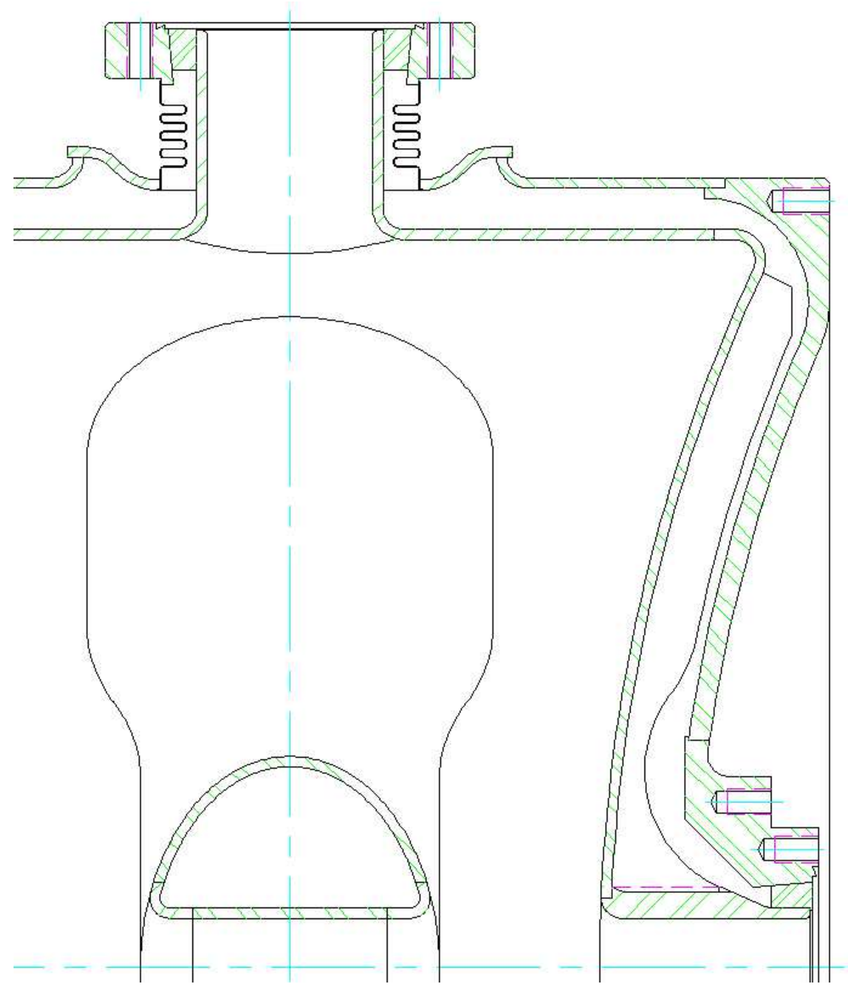
Flange Design

• each cavity has 2 beam flanges (3.37" or 4.5" CF) and 3 side flanges (4.5" CF)

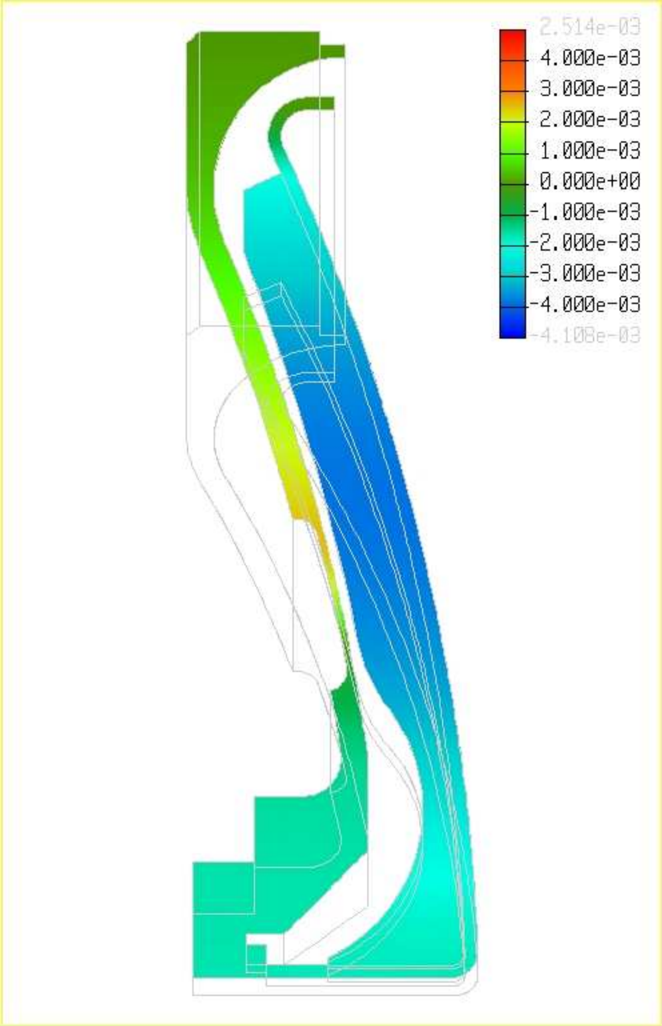
• 316L SS CF flanges brazed to Nb ring at 982 C using 82% Au, 18% Ni alloy (mp 949 C)

• excess Nb keeps temp below 700 C during ebeam weld, is machined away after welding





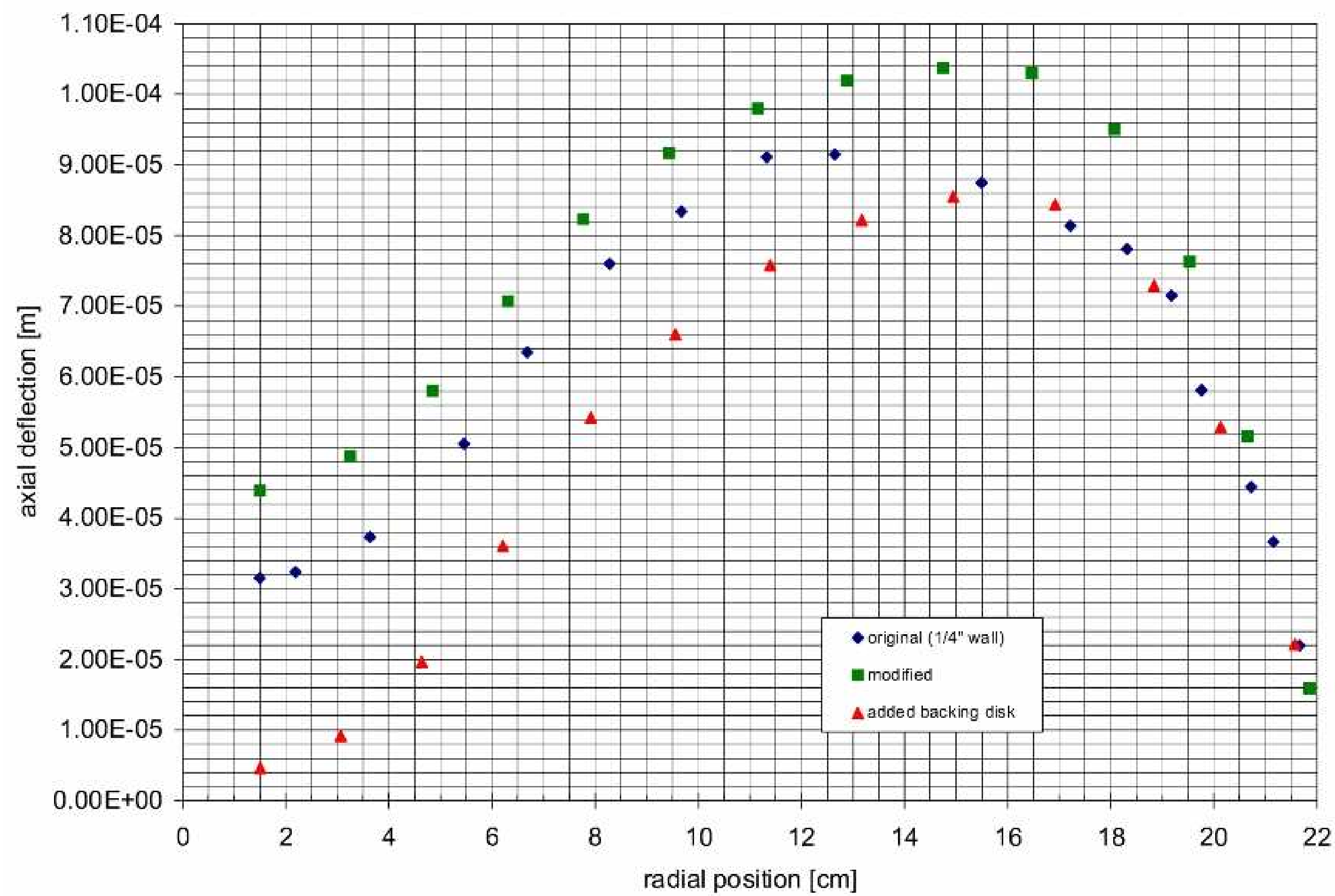
Displacement due to 15 psi load for alternative SS head geometries



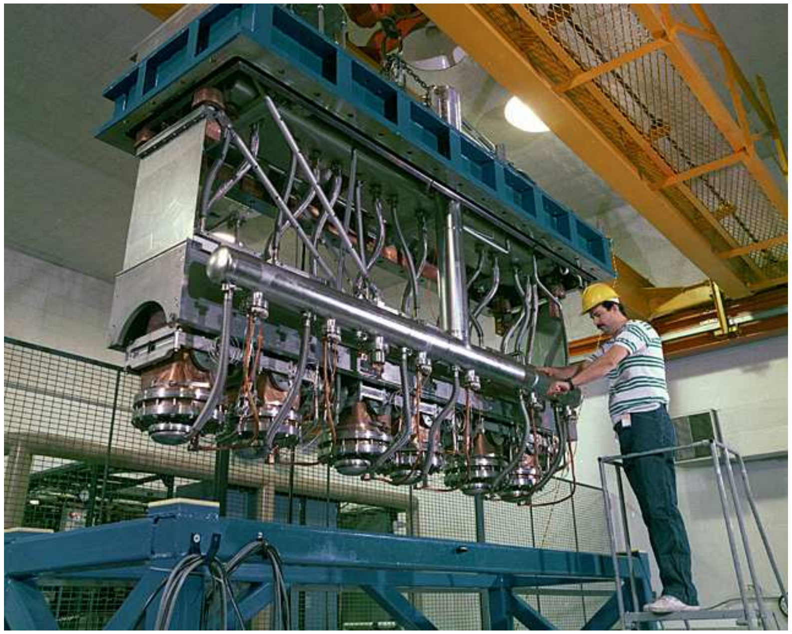
$\Delta f/f = -1.43E-5$

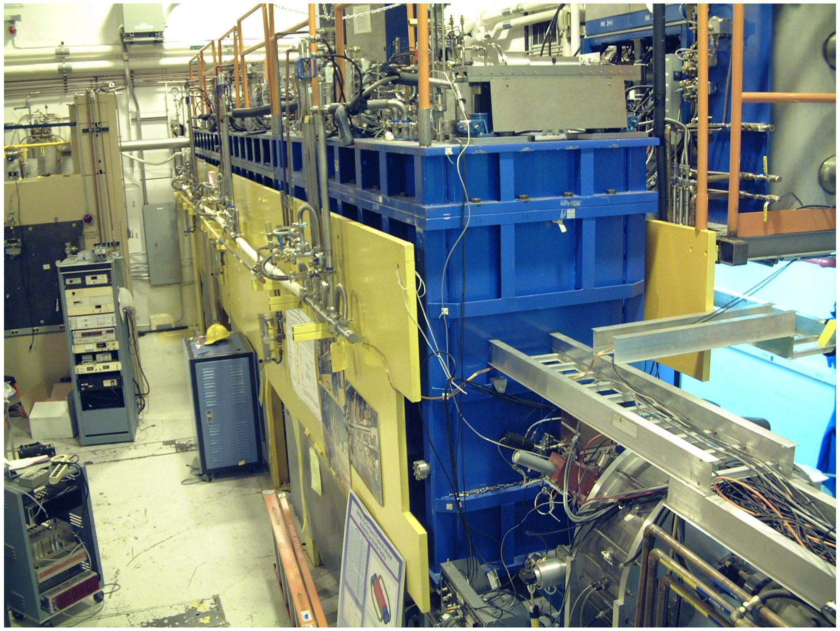
$\Delta f/f = 6.86E-6$

Endwall displacements



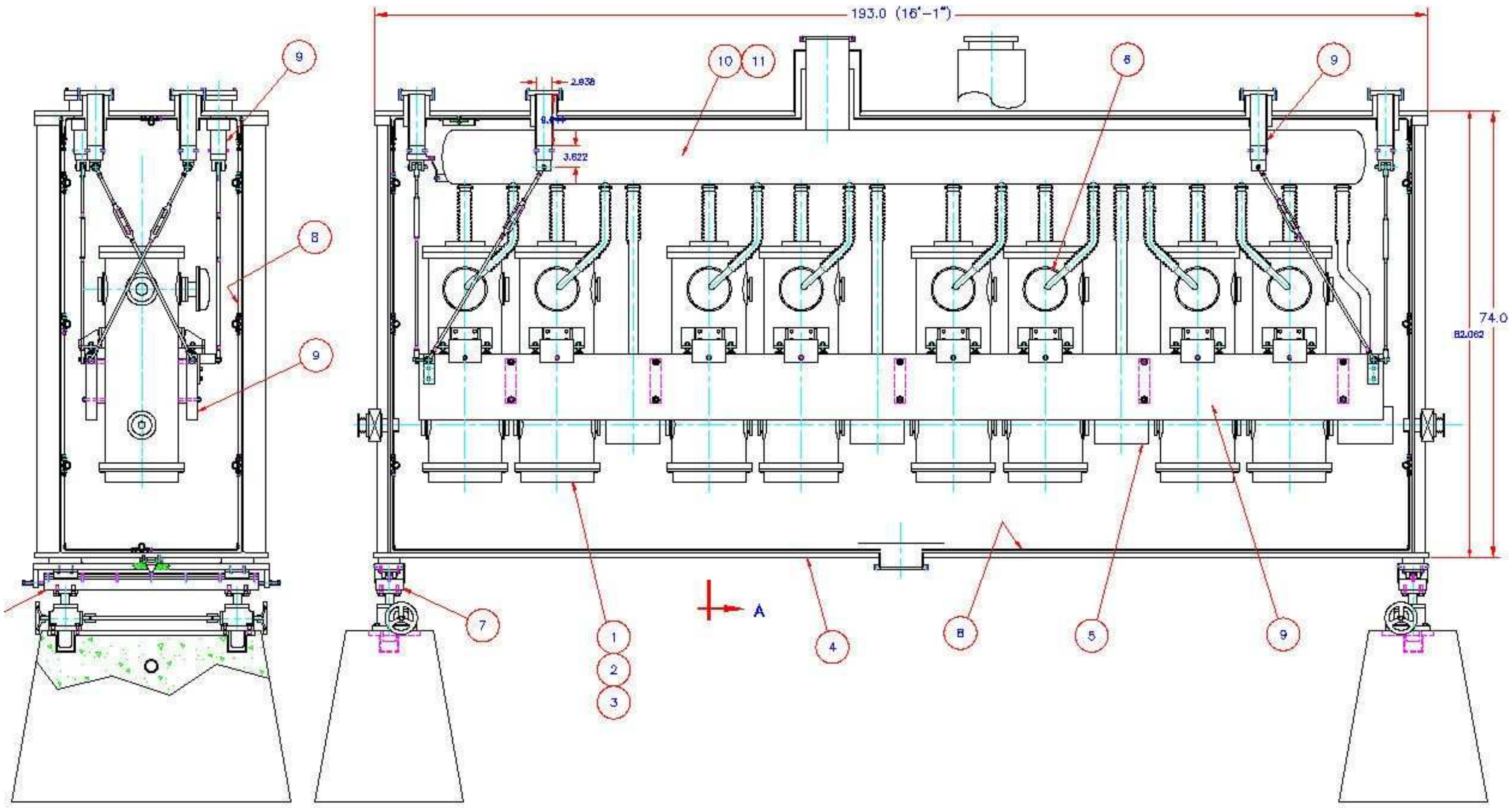
ATLAS Positive Ion Injector Cryomodule





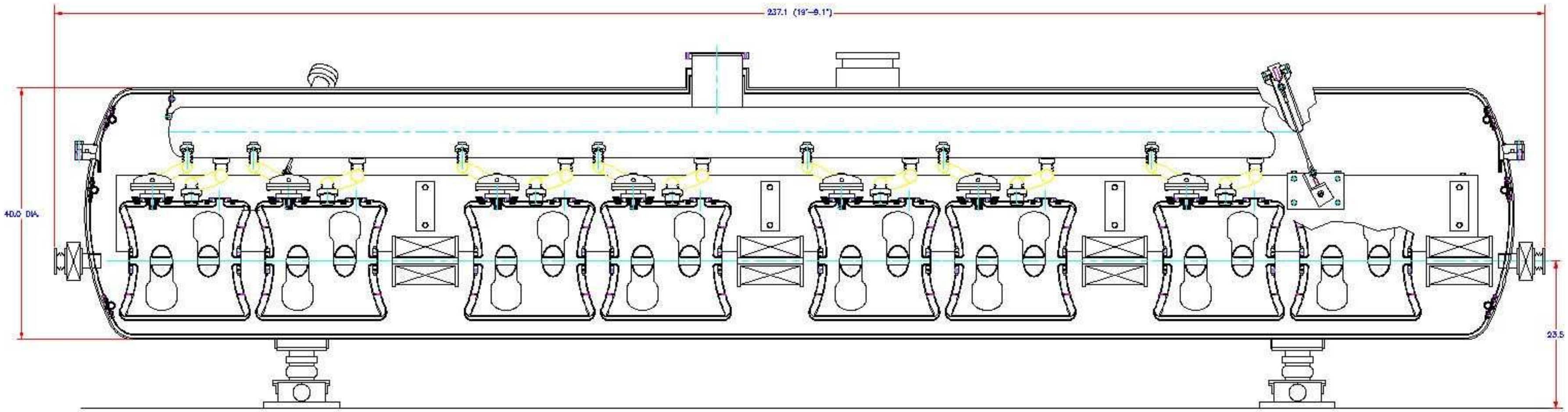
- Space efficient design
- Top loading
- Versatile
- Straightforward alignment capability

Design Evolution

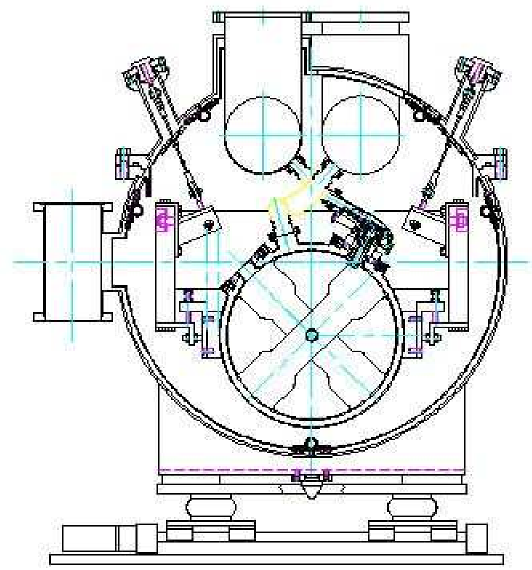


- •Based on ATLAS PII cryomodule
- •Top loading
- •Common vacuum vs. separate vacuums: cleanliness
- •Length is driven by cost, handling issues

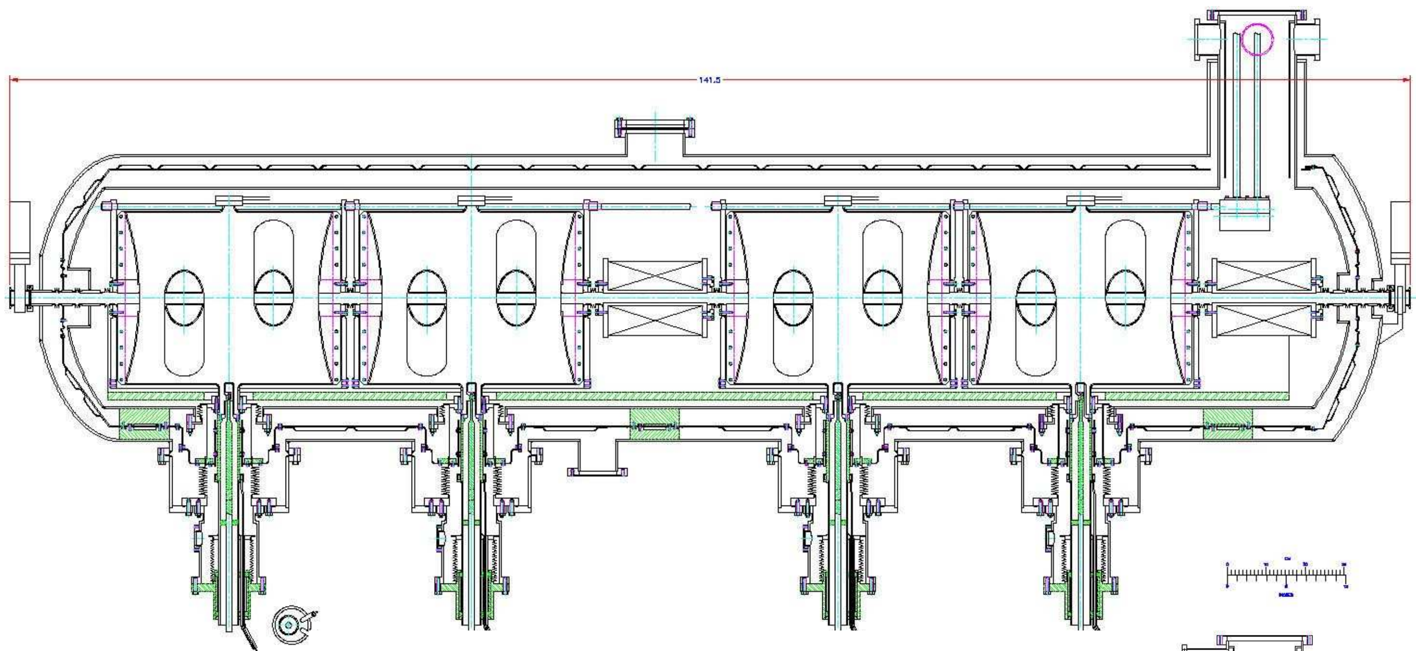
Design Evolution



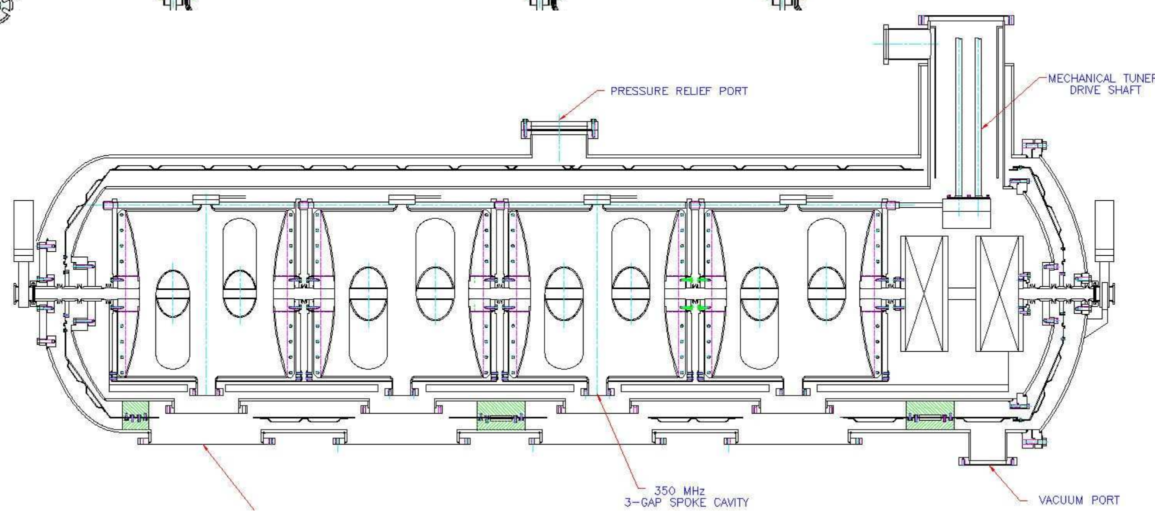
- Cylindrical
- Common vacuum
- Top loading



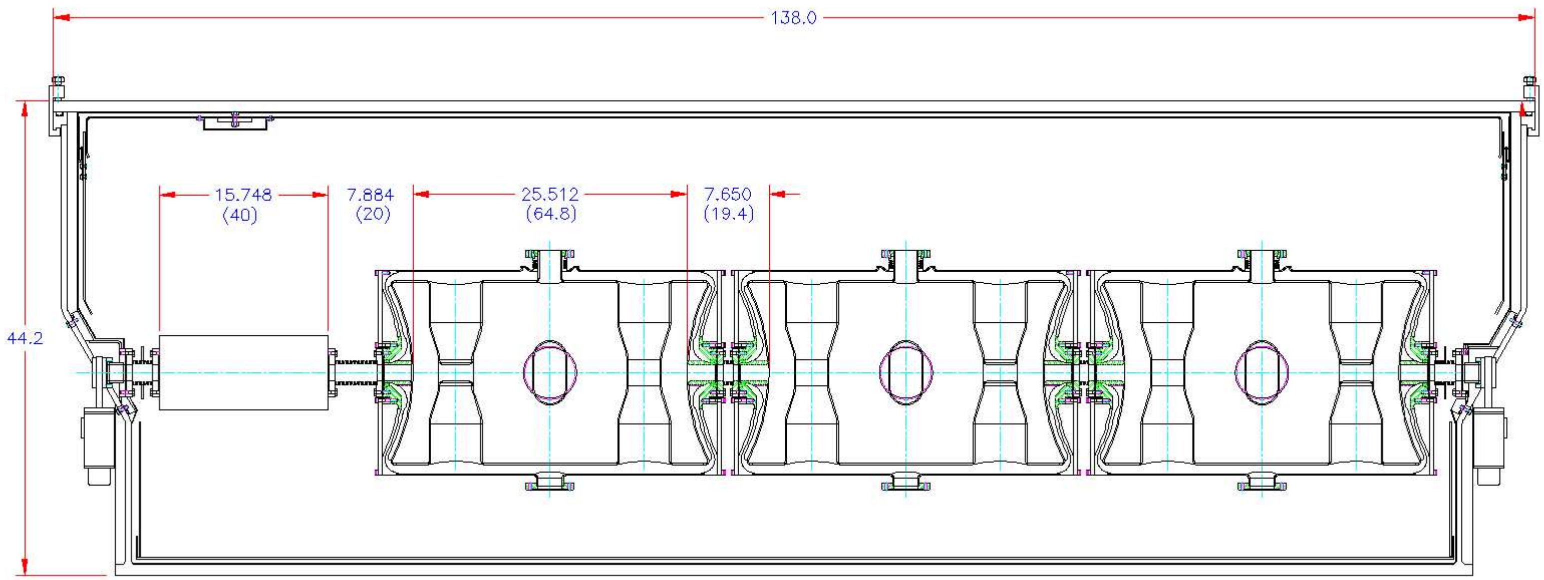
Design Evolution



- Cylindrical
- Separate vacuums
- End loading

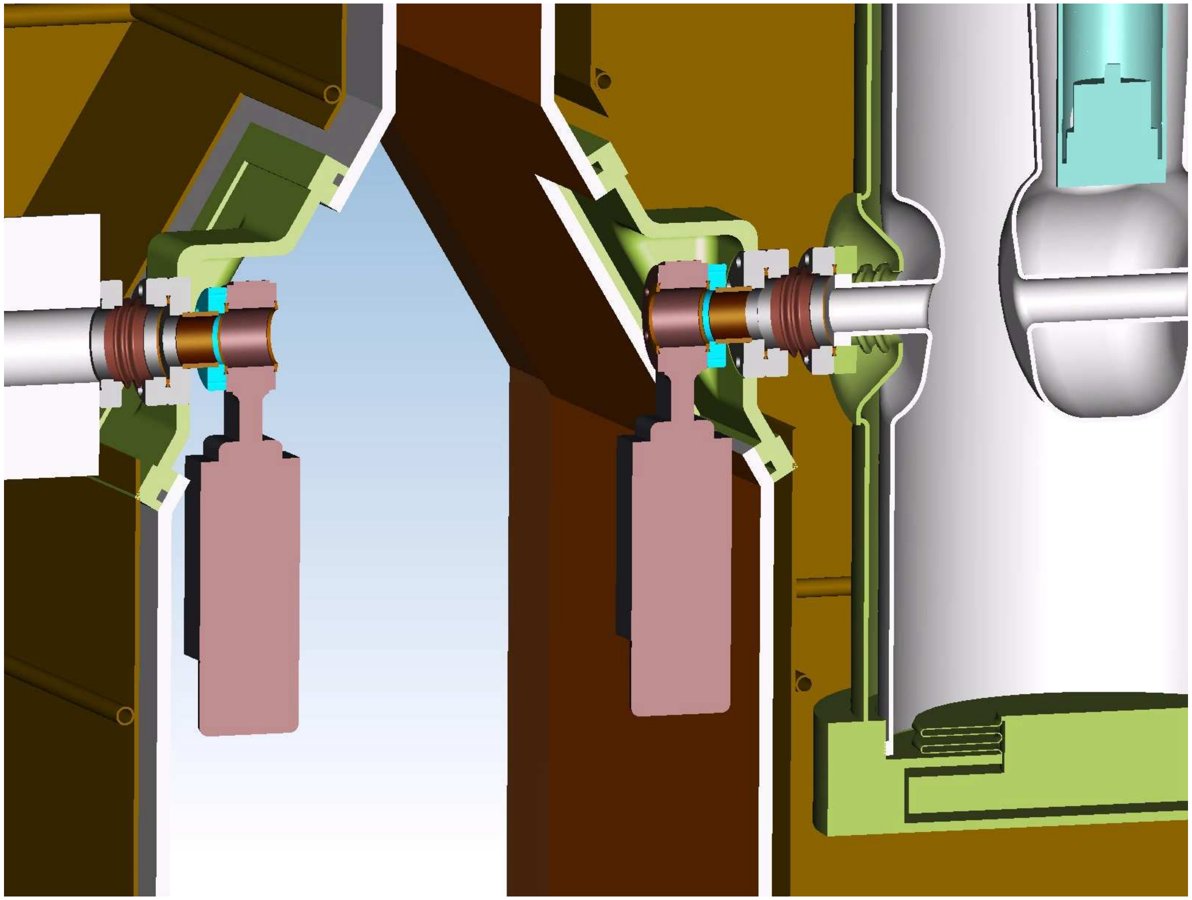


Box Cryomodule with Separated Insulating and Beam Vacuums



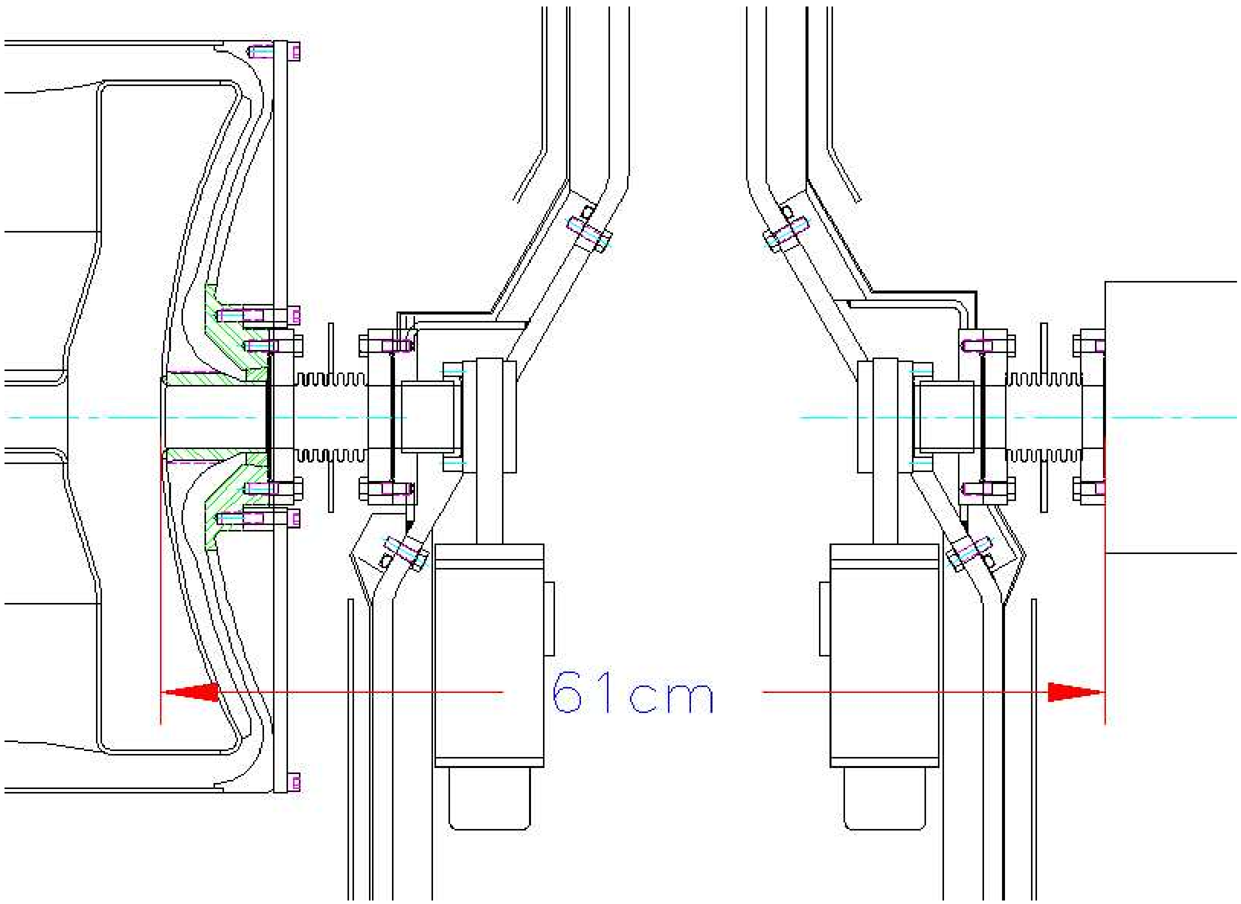
- Reconciles separate beam and insulating vacuum spaces with short module-to-module spacing
- Constructive feedback from JLab, DESY

Separate insulating and beam vacuums

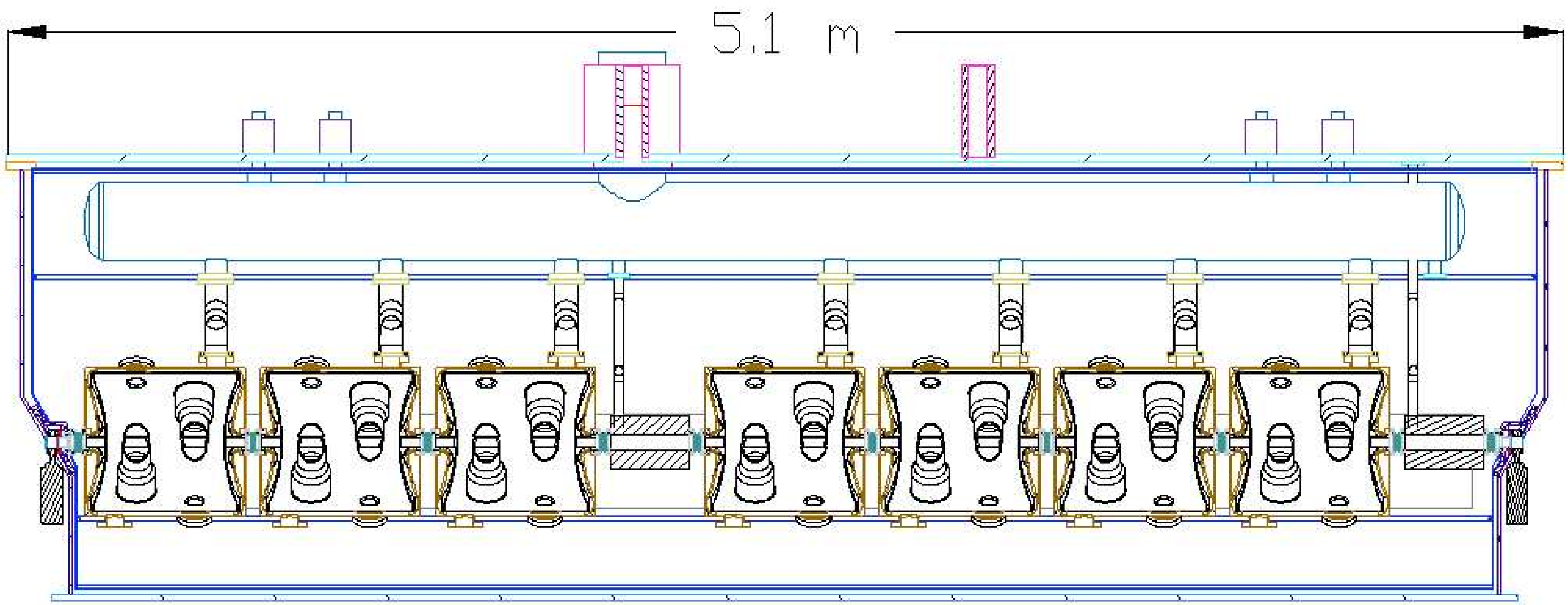


- Angled end walls permit drop-in installation
- Valves isolate clean components during final assembly
- Cleanliness requirements on vacuum vessel are relaxed
- Allows use of multilayer insulation

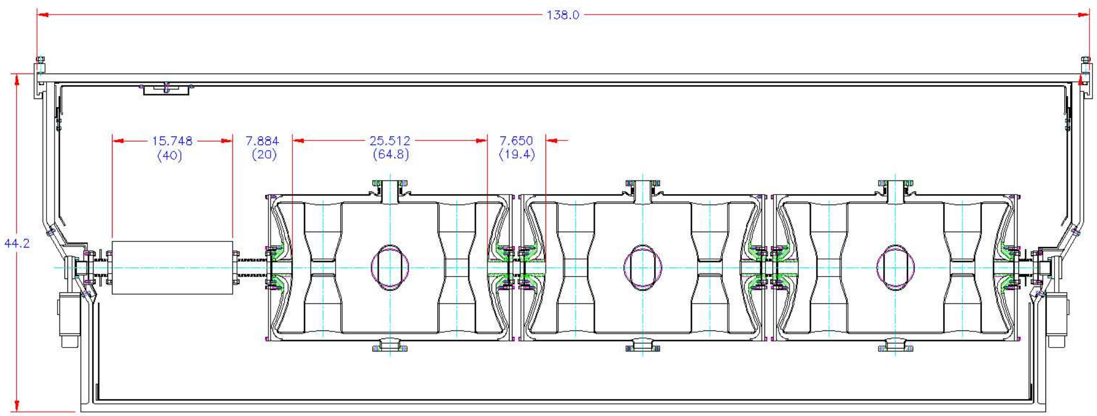
Module-to-Module Detail



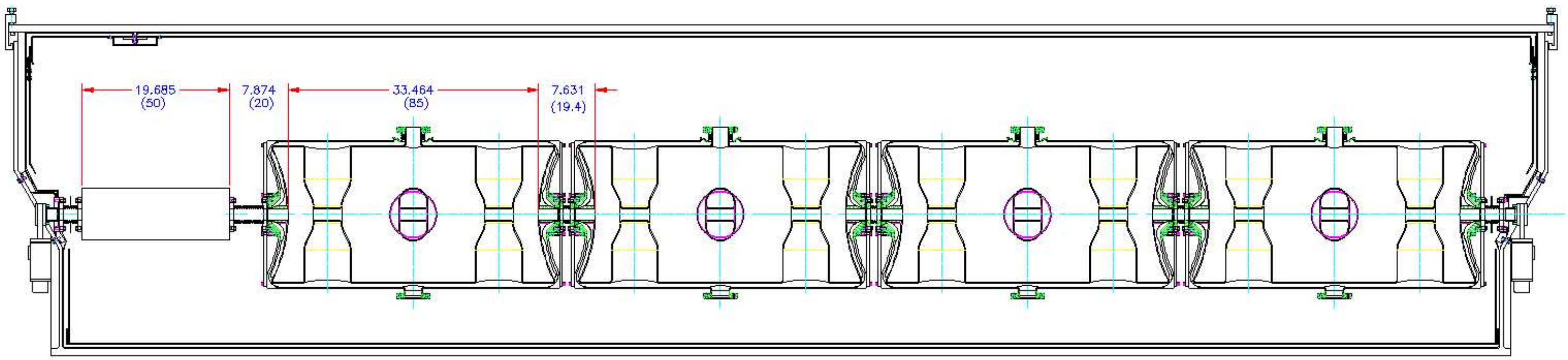
345 MHz β=0.36 Box Cryomodule



3-Spoke Cryomodules



β = 0.50



β = 0.62

Conclusions

- Box cryomodule concept builds on successful ATLAS PII design, end-loading cylindrical designs are proven at TTF, JLab, SNS, etc.

- Although rectangular shape is a good fit for a variety of drift tube cavity geometries, cylindrical may be more appropriate for spoke cavities

- Addresses gradient issue with separate beam vacuum and clean assembly techniques

- Preserves tight module-to-module spacing in a top- or end- loading design with separate vacuum systems

Discussion on "RIA Cryomodule Design Work" by Joel Fuerst

The first discussion focused on the integrated stainless/niobium helium vessel concept. Fuerst answered to a question that no bellows is incorporated into the vessel. The differential contraction for the 2-spoke case is acceptable. The resulting compression during cool-down is a small fraction of the slow tuner range. For the 3-spoke case this might have to be revisited.

The discussion elaborated on the concept of the integrated cavity/vessel design. The concept strives to balance the forces so that the vessel is stiff against helium pressure fluctuation but still has a low tuning force. This is not achieved by making the vessel inherently stiff against helium pressure, but by a design that is flexible and has a net cancellation of pressure deformation effects. This flexibility then allows low tuning forces. It was reiterated that this concept only compensates the helium pressure effect, any differential shrinkage effects due to cool-down still need to be taken care of by the slow tuner.

While there are no bellows in the helium vessels, there are bellows between cavities that allow an independent tuning of each cavity in a cryomodule. Related to this the cryomodule layout presented triggered questions about the assembly. The space between cavities is very tight. To study the feasibility it was suggested to build a mock-up for developing assembly procedures.

Pagani reported that for the present tuner in the TESLA design the Lorentz Force coefficient (LFC) is dominated by the "weak" tuner. This indicates that all auxiliaries to a cavity need to be considered when the dynamics of mechanical behavior is determined. Shepard answered that this is not an issue for RIA. Their design does not expect any additional stiffening from the tuning system itself at this time. The LFC results presented for the RIA cavities are for unconstrained cavities. These do not show any LF detuning issues. Any additional constraint will make the situation only better. He also added that LF detuning is less of an issue for the cw operation in RIA than it is for SNS, which is a pulsed machine.

The tuner discussion was closed by some remarks on the implications of a weak tuner. The use of such a tuner limits its use to very slow tuning, which is compatible with the concept of the RIA design.

Next the static losses of the RIA cryomodule were discussed. The dynamic losses per cavity are expected to be around 10 W. The static losses are expected to be around 1-2 W. Vogel commented that this sounds extremely good and asked if these could really be achieved. Also Kelley estimated that for the number of penetrations and details of their fixtures he would expect a higher number (around 30% of the dynamic losses). Shepard explained that these numbers are based on their operation experience with ATLAS. He conceded however that the final determination of this number can only be done when the system components are finalized.

Differential contraction behavior was the last topic discussed. Shepard explained that everything will be installed onto 2x12 aluminum strongback beams. This will drive all differential contraction. The cryo-connections will not be a problem, as they will all be flexible hosing.

XADS/Eurisol Cryomodule - Options for a Highly Reliable Spoke Linac

Jean-Luc Biarrotte, CNRS, IPN Orsay

The concept of reliability is a crucial issue for the XADS project, since the accelerator specifications ask for less than 5 beam trips per year. In that sense, CNRS proposed a spoke-based design for the “intermediate section” (5-100 MeV) of the proton linac, trying to take care as much as possible of this high-reliability challenge. In this presentation, a few basic arguments are developed around this item, especially concerning beam dynamics issues and their consequences on the design of such a spoke cryomodule.

Topic: Cryomodule

"Options for a Highly Reliable Spoke Linac"

J-L. Biarrotte – IPN Orsay

PDS-XADS

EURISOL

IPN Orsay Division Accélérateurs

CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

IN2P3 Institut National de Physique Nucléaire et de Physique des Particules

About the reliability issue

XADS linac specifications: less than 5 beam trips (>1s) per year !!!

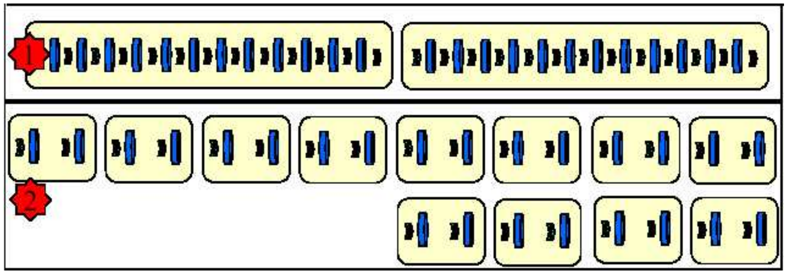
- **Over-design** and **redundancy** are very important criteria to follow in the linac design

- **High accessibility** is required for repairing or substitution “on-line”, without interrupting the beam

- The linac must tolerate the failure of most of the components**: a “fault-tolerant” design** has to be ensure whenever possible…

Basic choices for a reliable & fault-tolerant design

- **Focusing design**



⇒ **Small independent modules**: lattice length continuity, modularity, simplicity

⇒ **SC quadrupole doublets:** more matching capability than solenoids

- **Cavities**

⇒ **small number of gaps (2):** higher energy acceptance, higher capability for fault-tolerance, simplicity

- **Beam dynamics**

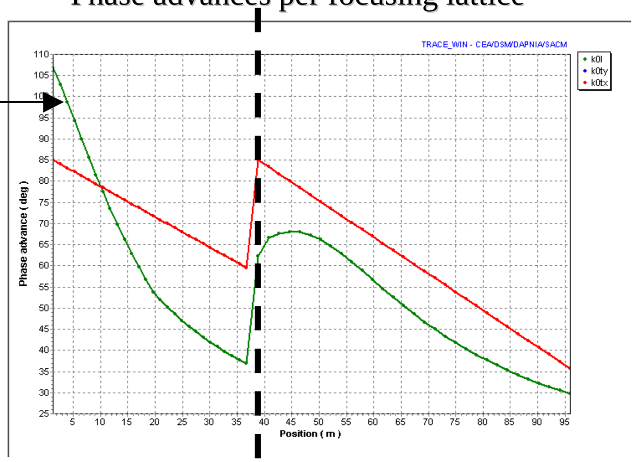
⇒ **Capture at 5 MeV**: synchronous phase ramped from –65° to –30°

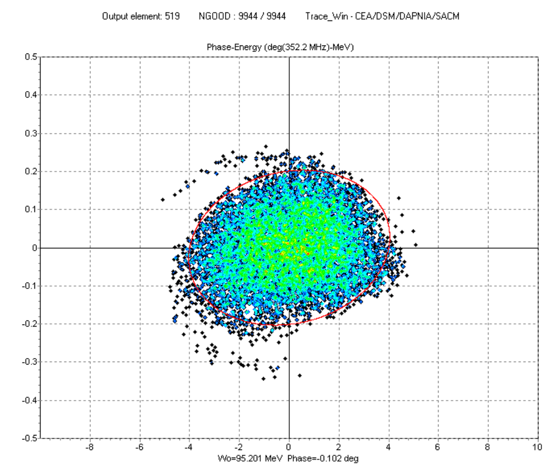
⇒ **Limit the accelerating gradient (thus σ) per focusing lattice:** 2-gap is far enough, and 1 (resp. 2) cavity per focusing lattice in the β=0.15 (resp. 0.35) section

& even the 2-gap case needs gradient limitations…

Phase advances per focusing lattice

Without limiting Eacc (Epk=25MV/m)

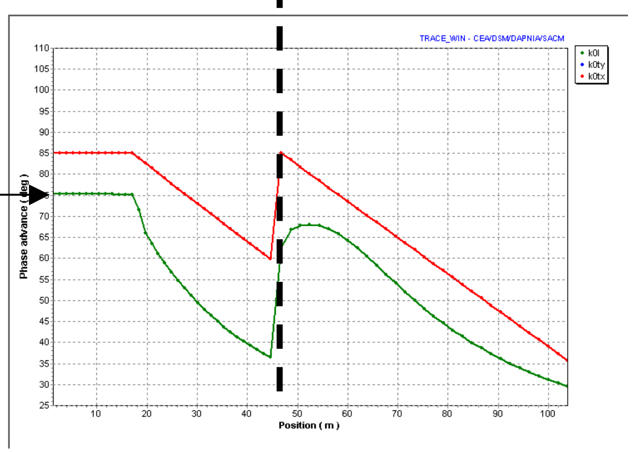


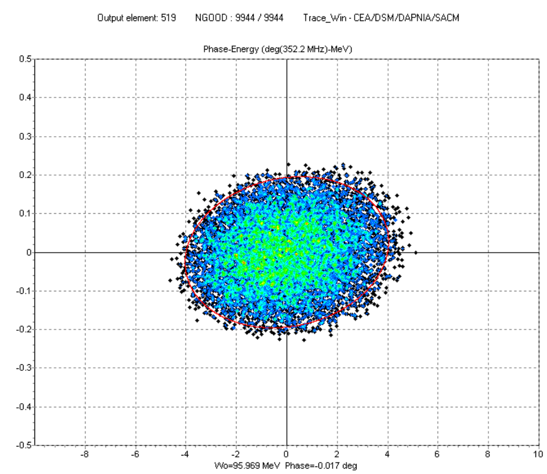


β=0.15 section
1 cav./lattice

β=0.35 section
2 cav./lattice

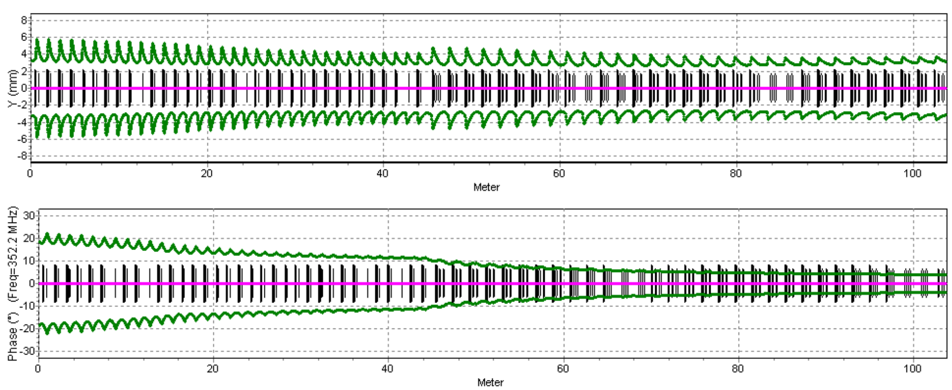
Limiting Eacc

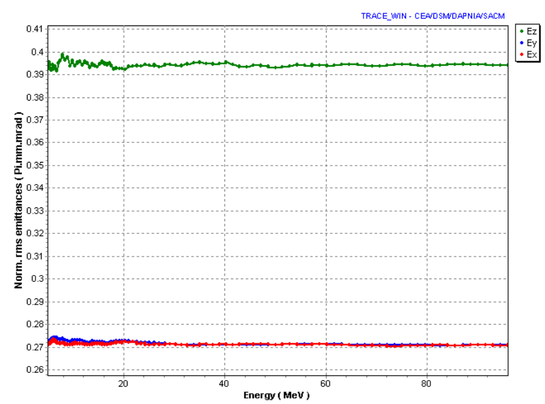




Proposal for a 5-95 MeV Spoke Proton Linac

Beam intensity: 10 mA CW	**"β=0.15" section**	**"β=0.35" section**
Energy range (MeV)	5 – 17	17 – 95
# Cavities	34	62
# Cavities per focusing lattice	1	2
Focusing lattice length (m)	1.3	1.9
Synchronous phase	- 65° to - 30°	- 30°
Energy gain per real meter (MeV/m)	0.06 – 0.38	0.31 – 1.58
Beam loading RF power (kW/cavity)	0.8 – 5.0	4.1 – 15.0
Quadrupole gradient (T/m)	17 – 24	24 – 35
Overall length (m)	44.2	58.9

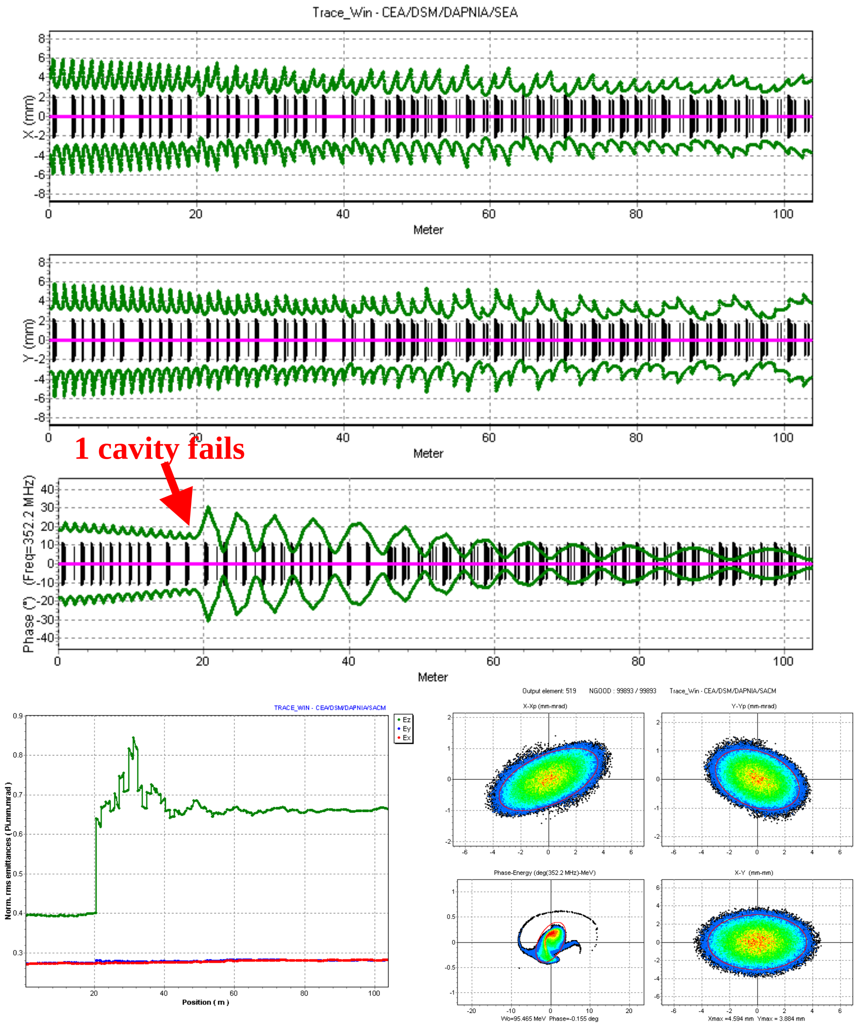




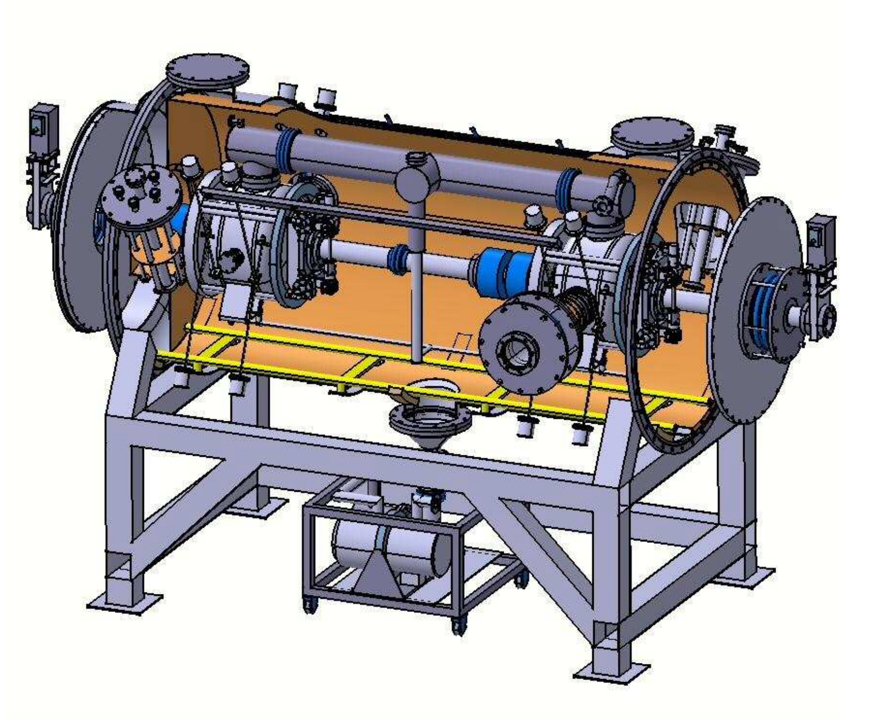
Advantages towards the reliability issue

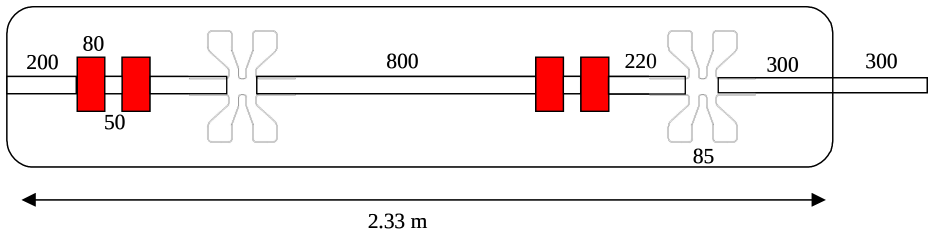
- 2-gaps cavities, independently powered
- Large beam apertures (>50mm)
- Very smooth and safe focusing design
- Modular & simple structures
- Possibility of intrinsically redundant design
- Fault tolerance capability

BUT… not very efficient in terms of real gradient between 5 & 25 MeV (β=0.15 section)



β=0.15 Spoke Cryomodule Prototyping (1)

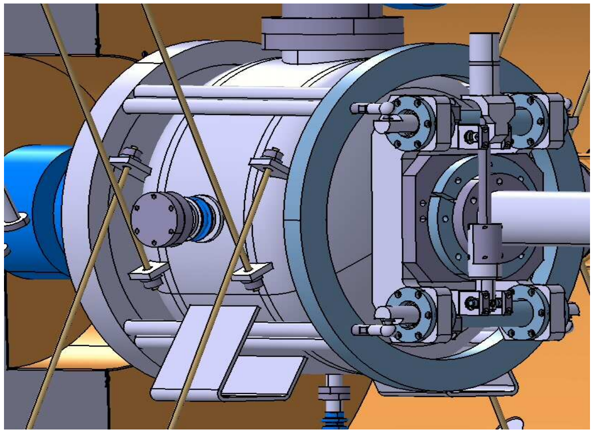


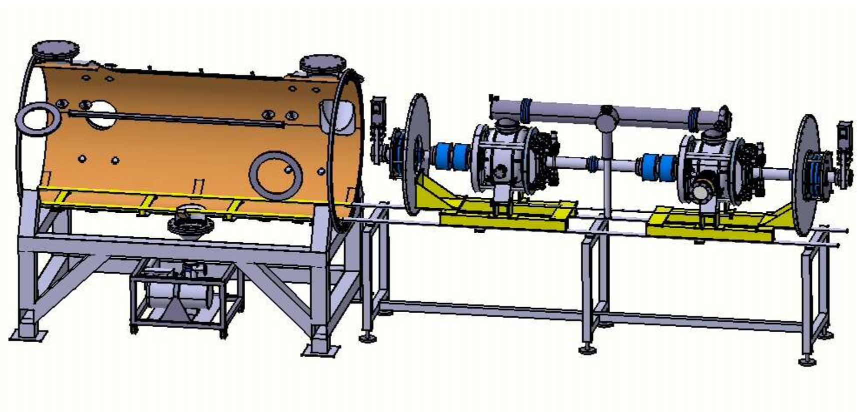


- 2.4 m long & 1 m diameter
- Including two 350 MHz spoke cavities
- Classical 4 K, 1 atm He bath
- Independent RF powering (≤5kW/cavity) using coaxial lines
- Focusing using two SC quadrupole doublets

SC « superferric » quadrupole (MSU-LNL)

β=0.15 Spoke Cryomodule Prototyping (2)





- **Cold Tuning System**: “SOLEIL-like”; efforts are applied on the flanges via Ti rods
- **Alignment** possible from the outside using 8 epoxy supports
- **Assembly**: 2 options are foreseen (whole mounting in a clean room or not)
- **Thermal shielding**: 2 options are foreseen (80 K circuit & multi-layer insulation)

Conclusion & perspectives

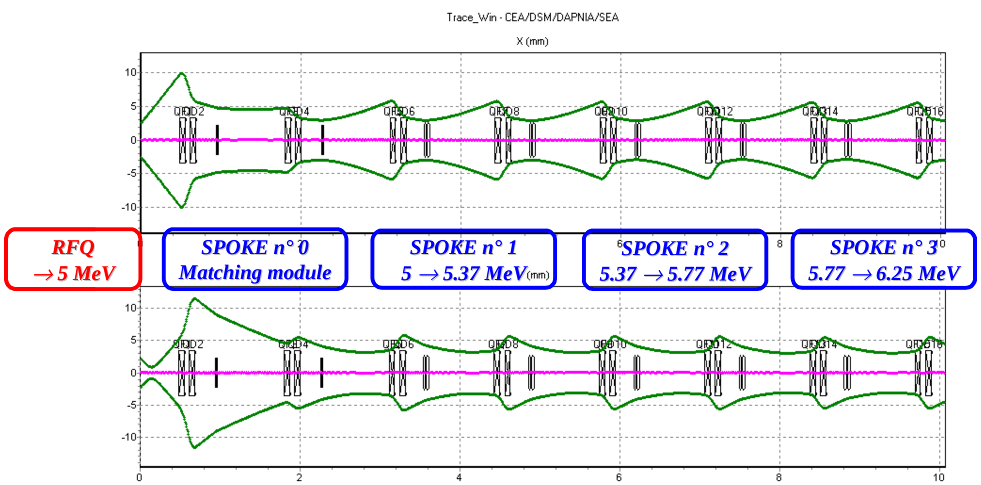
- The **preliminary design of a β=0.15 module** has began, and tries to fit with the XADS reliability requirements

- The aim = fabrication of a first prototype of cryomodule, which allows to test a few **different technological options**

The future =

- **Test with beam** (IPHI) without the need of a specific matching section

- Campaign for **testing the reliability of all the components**



Discussion on "XADS/Eurisol Cryomodule - Options for a Highly Reliable Spoke Linac" by Jean-Luc Biarrotte

The first discussion related to the real estate gradient of the low end of the accelerator, right behind the RFQ. This gradient starts out at only 0.3 MV/m and increases through the spoke section to 1 MV/m. This is mainly driven by the fault tolerant short lattice. Facco points out that this high reliability concept was first proposed for TRASCO. The implementation by Legnaro is different however. XADS/Eurisol uses 2-gap spokes with doublet focusing, while TRASCO uses 1-gap (re-entrant) cavities with singlets. The TRASCO implementation is only half as long as the spoke implementation.

Biarrotte next explained that the free space in some of the cryomodules is also resulting from the reliability concept, that uses a continuous lattice length for high beam quality. They are using quads instead of solenoids for focusing. The beam quality is very similar and quads give more flexibility by allowing to independently focus in both transverse planes. The focusing lattice is not independently optimized for the XADS application. This is only done for the demonstration machine. The final ADS machine would have an dedicated optimized lattice.

Pagani pointed out that for the European ADS work the final scheme is still under discussion. While the two main sections above 20-25 MeV are more or less set (2-gap or 3-gap spokes up to 100 MeV and then 2 or 3 different elliptical cavity types), the low energy end up to 20 or 25 MeV is still totally open.

ADTF Spoke Cavity Cryomodule Concept

P. Kelley, Los Alamos National Laboratory

The Accelerator Driven Test Facility (ADTF) is being developed as a reactor concepts test bed for transmutation of nuclear waste. A 13.3 mA continuous-wave (CW) proton beam will be accelerated to 600 MeV and impinged on a spallation target. The subsequent neutron shower is used to create a nuclear reaction within a subcritical assembly of waste material that reduces the waste half-life from the order of 105 years to 102 years. Additionally, significant energy is produced that can be used to generate electrical power.

The ADTF proton accelerator consists of room-temperature (RT) structures that accelerate the beam to 6.7-MeV and superconducting (SC) elements that boost the beam's energy to 600-MeV. Traditional SC elliptical cavities experience structural difficulties at low energies due to their geometry. Therefore, stiff-structured SC spoke cavities have been adopted for the energy range between 6.7 and 109 MeV. Elliptical cavities are used at the higher energies. This paper describes a multi-spoke-cavity cryomodule concept for ADTF.

Spoke Cavity Cryomodule Concept for the Accelerator Driven Test Facility (ADTF) Low Energy Linac (LEL)

J. Patrick Kelley

October 8, 2002

Major Contributors

Phil Roybal, Mechanical Design, TechSource
Richard LaFave, Stress Analysis & Alignment, Formerly of LANSCE-1
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Joe Waynert, Coupler Thermal Analysis, ESA-AET
Dale Schrage, LEL Lead, LANSCE-1
Eric Schmierer, Coupler, ESA-DE
Frank Krawczyk, RF Physics, LANSCE-1
Bob Garnett, Beam Physics, LANSCE-1
Tsuyoshi Tajima, Cavities, LANSCE-1

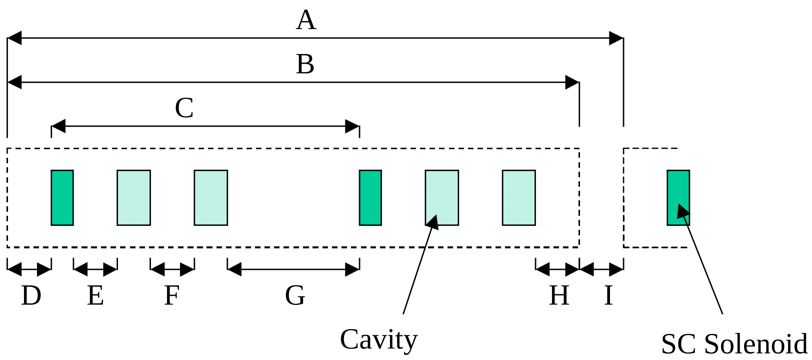
Introduction

- **The Accelerator Driven Test Facility (ADTF)**
  - **Is a reactor concepts test bed for transmutation of nuclear waste.**
  - **Uses a 13.3 mA (CW), 600 MeV linear accelerator to produce neutrons by spallation.**
- **The ADTF Low Energy Linac (LEL) uses 350 MHz superconducting (SC) spoke cavities between 6.7 - 109 MeV.**
- **Beam dynamics dictates that cavities of three β types be used:**
  - **β=0.175 two-gap cavities,**
    - » **A β=0.175 lattice element consists of a solenoid magnet and two cavities**
    - » **The focussing period is 2.26 m**
  - **β=0.2 and β=0.34 three-gap cavities,**
    - » **the lattice consists of a solenoid magnet and three cavities.**
    - » **The focussing periods are 3.05 and 3.46 m respectively.**

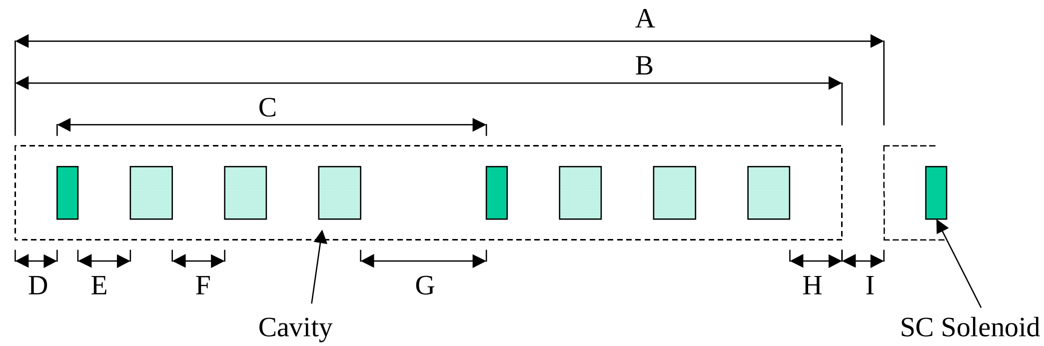
Spoke-Cavity Cryomodule Period

- **The cryomodule period was dictated by:**
  - **The need to reduce LEL length and total system costs by minimizing distances between elements.**
    - » **This led to inclusion of the solenoids as SC elements in the cryomodule.**
  - **The need for periodic warm spaces for beam diagnostics.**
  - **The desire to maximize cryomodule lengths to**
    - » **minimize the total number of warm to cold transitions,**
      - **reduce heat loads and cryogenic distribution system complexity.**
  - **The need to fit the module elements into the existing clean room.**

Spoke-Cavity Cryomodule Period



ß=0.175 Cryomodule



ß=0.2 or 0.34 Cryomodule

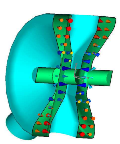
		β=0.175	β=0.2	β=0.34
Cryomodule Period	A	4.53 m	6.10 m	6.92 m
Cryomodule Length	B	4.23 m	5.80 m	6.62 m
Focusing Period	C	2.26 m	3.05 m	3.46 m
Warm to Cold Transition (1)	D	0.39 m	0.39 m	0.39 m
Magnet to Cavity Drift	E	0.3 m	0.3 m	0.3 m
Cavity to Cavity Drift	F	0.3 m	0.3 m	0.3 m
Cavity to Magnet Drift	G	1.11 m	1.11 m	1.11 m
Warm to Cold Transition (2)	H	0.42 m	0.42 m	0.42 m
Cryomodule to Cryomodule Drift	I	0.3 m	0.3 m	0.3 m
Magnet Physical Length		0.15 m	0.15 m	0.15 m
Cavity Physical Length		0.20 m	0.30 m	0.43 m

Spoke-Cavity Cryomodule Parameters

	β=0.175	β=0.2	β=0.34
Q_o	1.72 E 9	1.92 E 9	2.50 E 9
E_{acc}	5 MV/m	5 MV/m	5 MV/m
Frequency	350 MHz	350 MHz	350 MHz
Coupled Power @ 13.3mA(100 mA)	4.7 (35.3) kW	10.35 (77.8) kW	18.6 (139.8) kW
Cavity Operating Temperature	4.5 K	4.5 K	4.5 K
Cavity External Magnetic Field (Goal)	5 milli-Gauss	5 milli-Gauss	5 milli-Gauss
Cavity Mechanical Resonance	> 200 Hz	> 200 Hz	> 200 Hz
Tuning Stiffness	~ 26 kHz/mil 0.31 kHz/lb.	To Be Determined	To Be Determined
Cavity Detuning Rate in < 300 msec	67 kHz/sec 67 micron/sec	To Be Determined	To Be Determined
Shield Operating Temperature	40-55 K	40-55 K	40-55 K
Solenoid Field	1.8-2.32 T	2.5-4.0 T	4.0-5.4 T
Current	20 A	20 A	20 A
Lead Type	Conduction Cooled	Conduction Cooled	Conduction Cooled

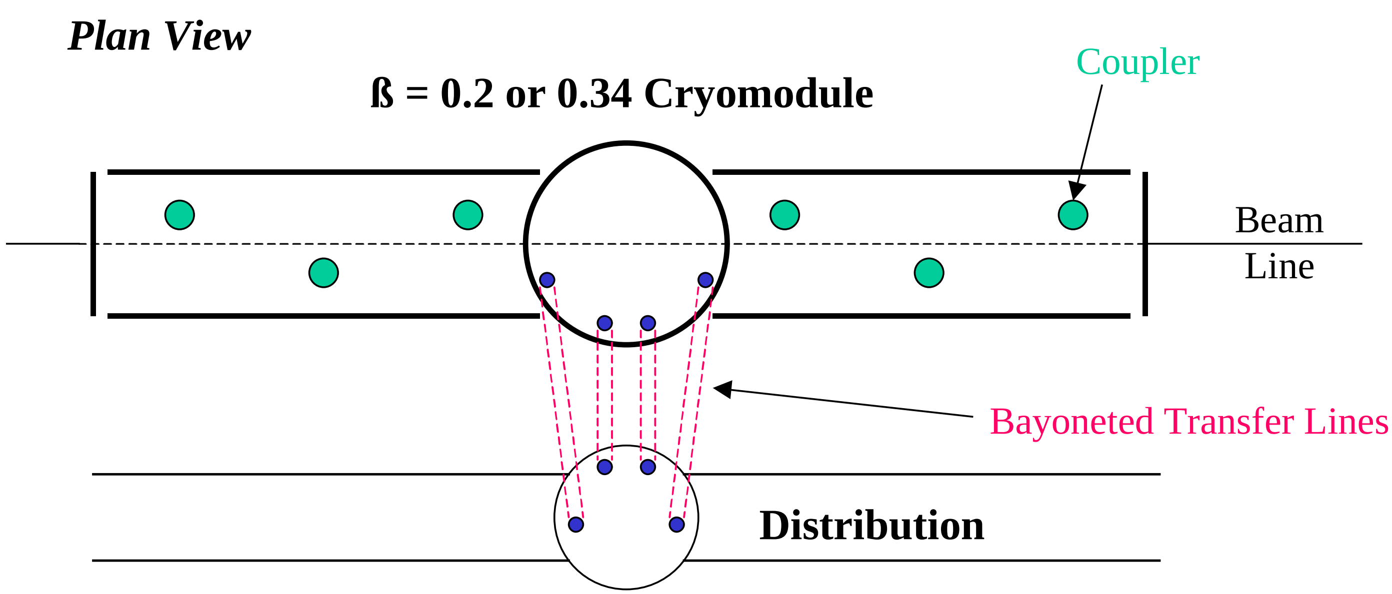
Cryomodule Design Goal and Guidelines

- **Goal: Provide a cryomodule design that can easily be built by industry.**
- **Focus of Presentation**
  - **ß = 0.34 Spoke Cavity Cryomodule.**
    - » **Elements are similar for all ADTF spoke cavity cryomodules.**
- **Basic guidelines used during cryomodule design development :**
  - **Adopt concepts and components from previous programs where possible.**
  - **Insert helium vessel assemblies axially into the vacuum vessel.**
    - » **Minimizes cleanroom time and simplify assembly**
    - » **Minimize radial penetrations is a corollary.**
  - **Adopt design similarity between the three module types.**
    - » **With the exception of length, parts should be identical.**
  - **Since ADTF has it roots in the Accelerator Production of Tritium Program (APT),**
    - » **It must be upgradable to 100 ma operations for tritium production.**
    - » **The ADTF cryomodule must fit into the APT tunnel design.**
      - **(After the completion of this work, this requirement was eliminated.)**



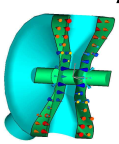
Spoke Cavity Cryomodule Form

- **Physical Form**
  - **Ingress and egress of cryogens at center of module**
    - » **Permits axial assembly approach**

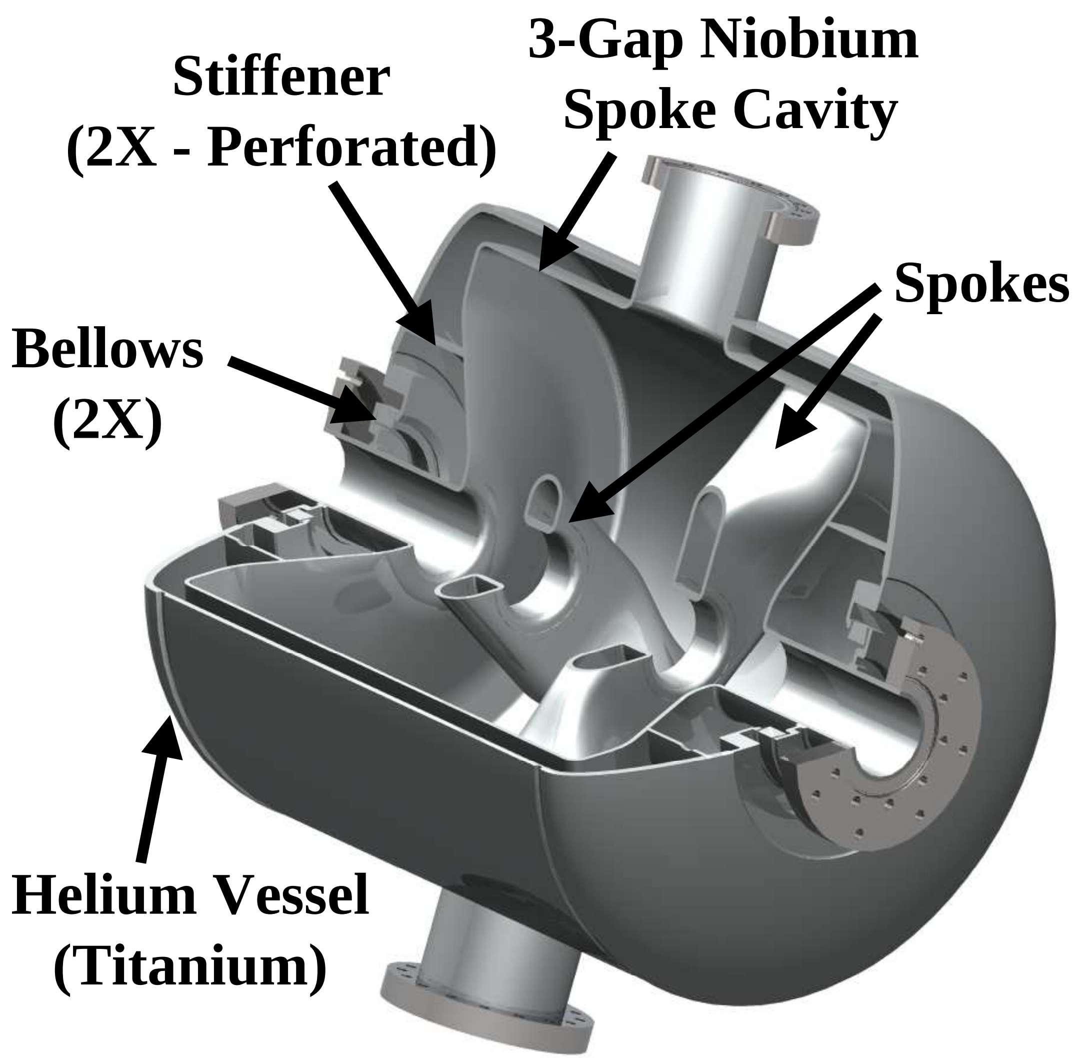


Tuners and Helium Vessels

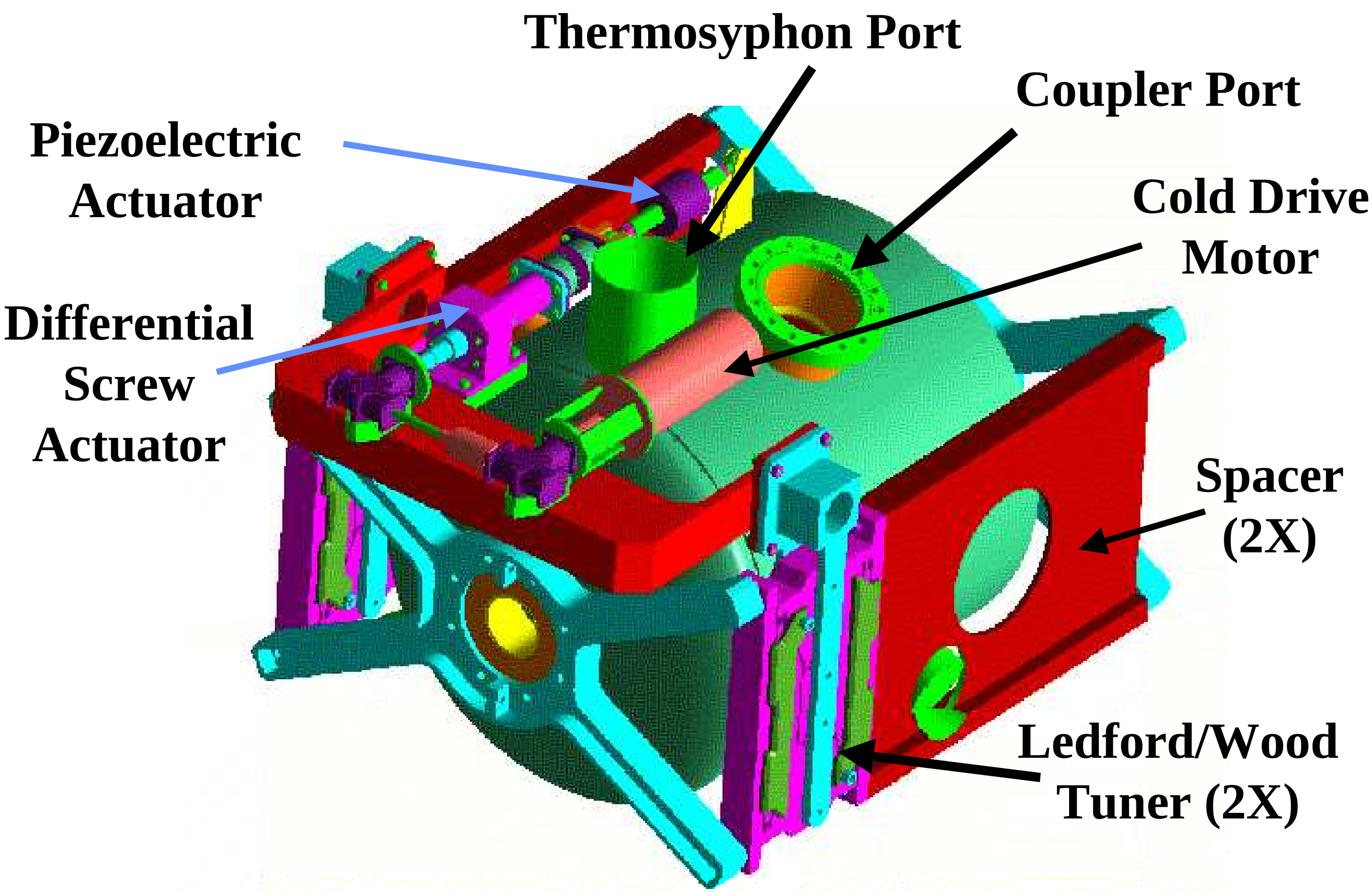
- **Cavities are tuned individually.**
  - **Both end walls of a spoke cavity must be flexed**
    - » **Tuner assembly must straddle the cavity.**
- **A cavity is housed in its own titanium helium vessel with the tuner outside the vessel.**
  - **If both cavity and tuner were housed in a helium vessel**
    - » **Helium vessel size would increase,**
    - » **Essentially flat helium vessel heads would be necessary to minimize spacing between cavities, leading to thicker material or elaborate stiffeners.**
    - » **Multiple cold penetrations would be required.**
  - **If multiple cavities with tuners were housed in a single vessel,**
    - » **The length dictates elaborate penetrations to handle thermal contractions.**
- **A Ledford/Wood tuner mechanism (APT program) was adopted.**
  - **The cavity stiffeners are used to transfer loads through the helium vessel.**
  - **Bellows are used to de-couple the beam tube from the helium vessel.**
  - **A cold stepper motor drives tuner. (Warm motor/axial drive shaft possible.)**
  - **A piezoelectric actuator is used to detune the cavity in < 300 msec.**



3-Gap Spoke Cavity with Helium Vessel



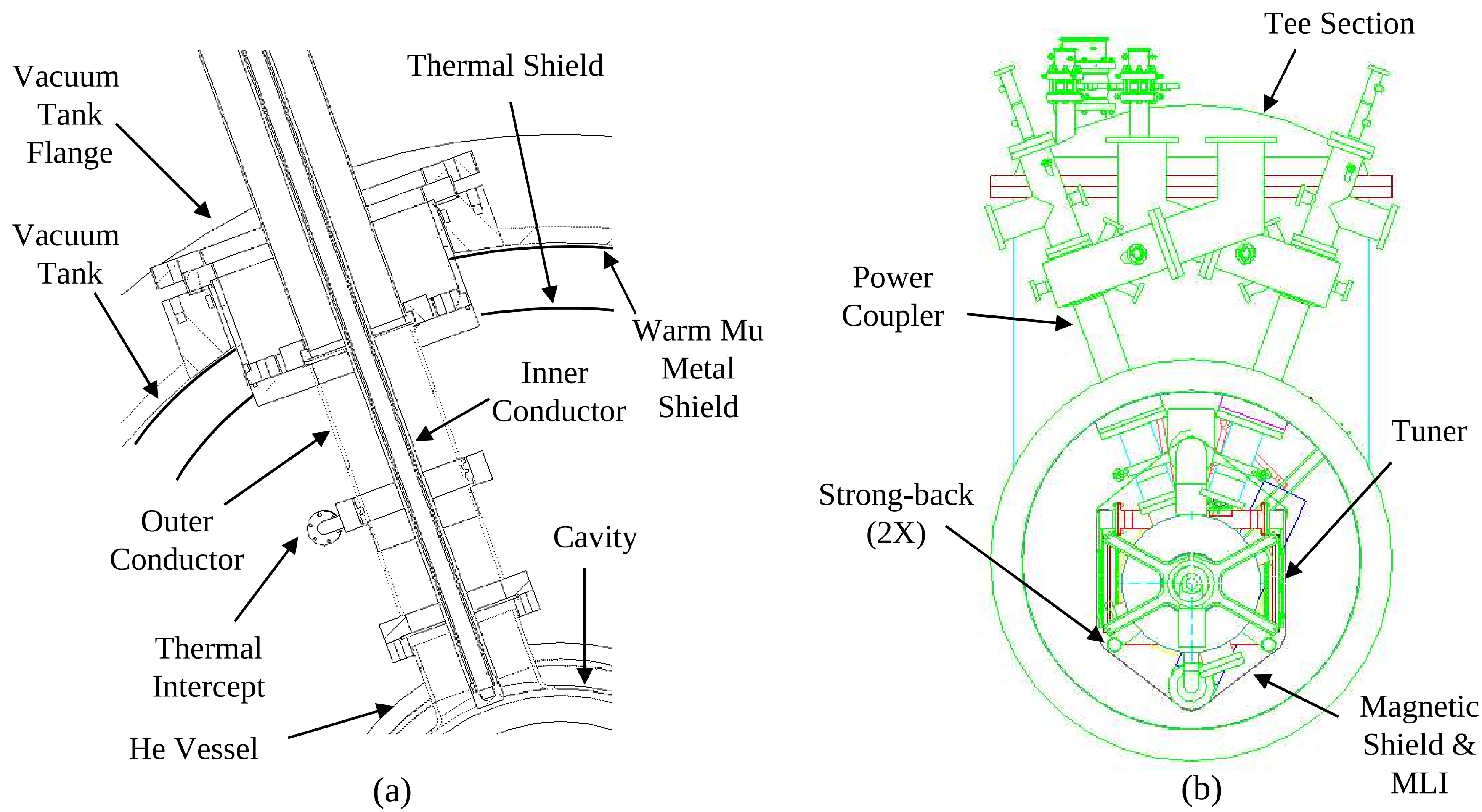
ß = 0.34 Spoke Cavity Helium Vessel with Tuner Assembly



Power Coupler

- The fixed power coupler is a 75 Ω, coaxial, unbiased unit.
- Couplers are oriented 20° from vertical, with adjacent couplers in a lattice on alternate sides of the module. The couplers closest to the center Tee section are on the same side of the module.
  - The near vertical orientation was due to APT tunnel constraints.
  - The alternating sides coupler arrangement is necessary to maintain clearance between large WR2300 waveguides (0.584 X 0.146 m.).
- Heat loads were calculated for a single point thermal intercept
- The coupler is also the only helium vessel assembly support structure, therefore simplifying assembly.
  - Assembly is simplified with fewer penetrations through shields and blankets. Fewer penetrations through the magnetic shields reduces magnetic-fringe fields.

Power Coupler

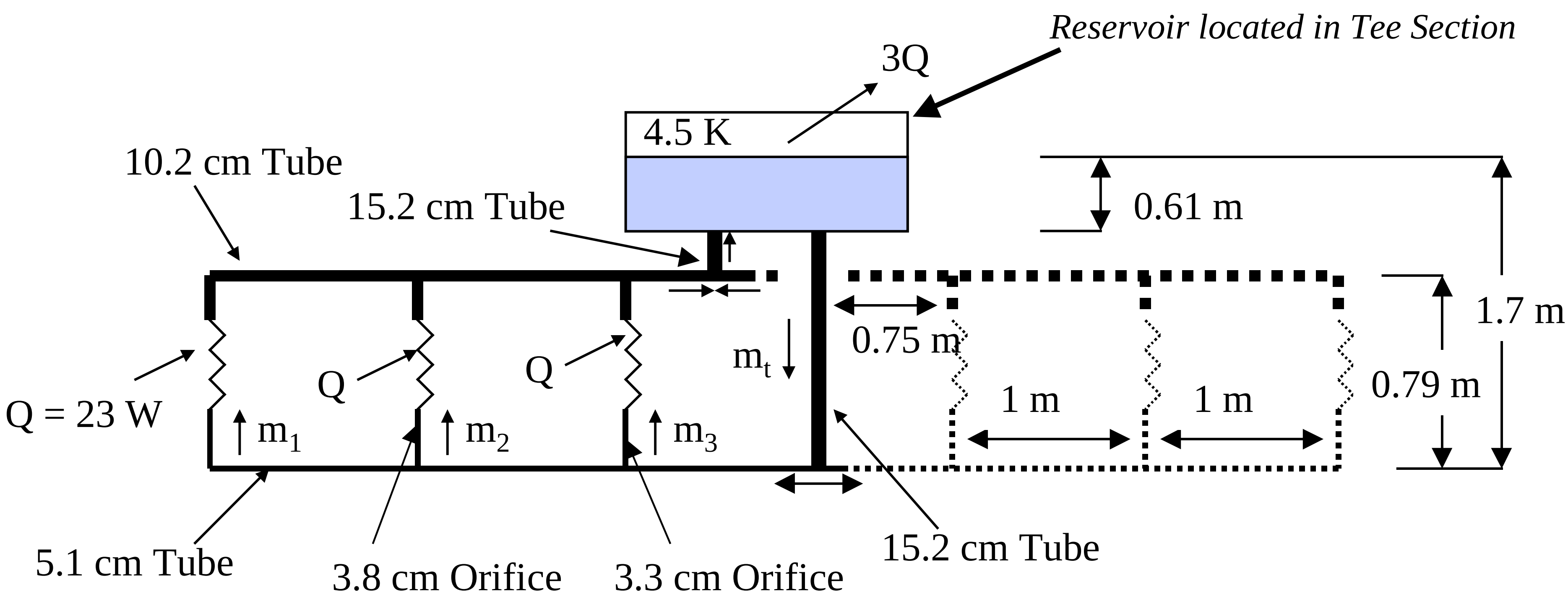


(a) Coupler - vacuum vessel interface. (b) Cryomodule section. Warm shields not shown.

Cavity Cooling Approach - A Thermosyphon

- **An open-loop thermosyphon cooling approach was selected to cool the spoke cavities.**
  - **Individual helium vessels limits the volume available for helium inventory.**
  - **At 4.5 K, bath cooling has better heat transfer properties than supercritical forced flow.**
    - » **boiling of the helium is anticipated with the potential for vapor trapping/locking.**
  - **A thermosyphon**
    - » **deals well with space constraints,**
    - » **provides reasonable helium inventory,**
    - » **reduces the potential for vapor locking and**
    - » **improves heat transfer through localized forced flow.**

Thermosyphon Analysis - 0.34 β Cryomodule



m_1 = 35.3 g/s, χ_1 = 0.028
m_2 = 35.2 g/s, χ_2 = 0.029
m_3 = 34.9 g/s, χ_3 = 0.029
m_t = 210.9 g/s

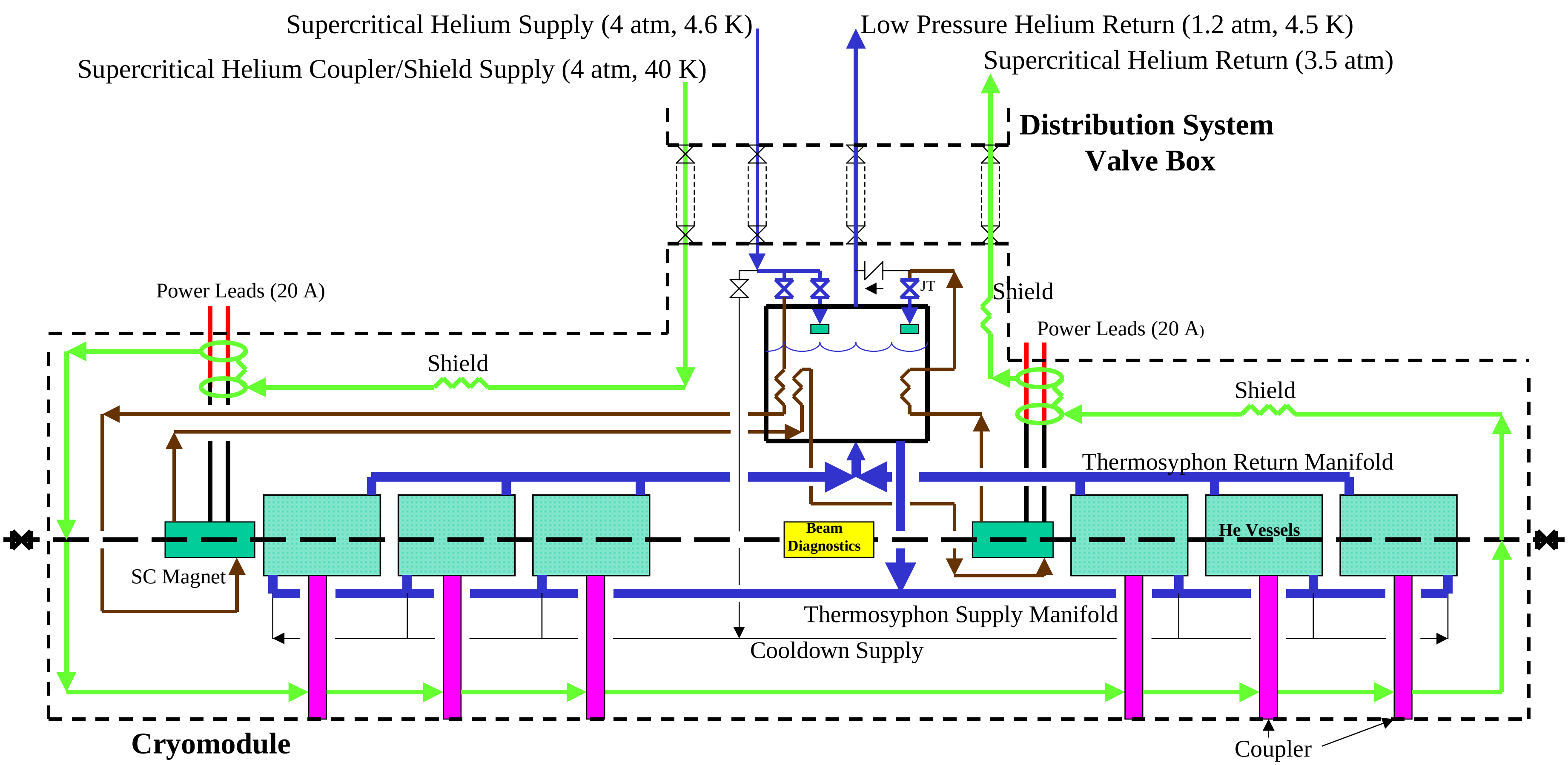
All tube 0.165 cm wall

Orifice plates balance flows through the legs.
χ - flow quality
Bellows in the runs between risers were included in the analysis but are not shown.

Cryogen Supply

- **Supercritical helium at 4.6 K and 4 atm is supplied to the module**
  - **The flow is split**
    - » **A portion expanded by a JT valve to fill the thermosyphon reservoir.**
    - » **The remaining flow is recooled and directed serially to the solenoids.**
      - **A recooler between magnets is sized so that the downstream magnet is not impacted by an upstream magnet quench.**
      - **A recooler after the downstream magnet removes quench or other heat from the flow, allowing the return of useful cold gas to the cryoplant.**
      - **The supercritical flow is then throttled to thermosyphon reservoir pressure to provide liquid, and to eliminate the need for a separate return line in the distribution system.**
- **The shields and intercepts are cooled by a flow of supercritical helium at 4 atm. and $40 < T < 55$ K.**
  - **Current leads are conductively cooled with a 40 K intercept.**

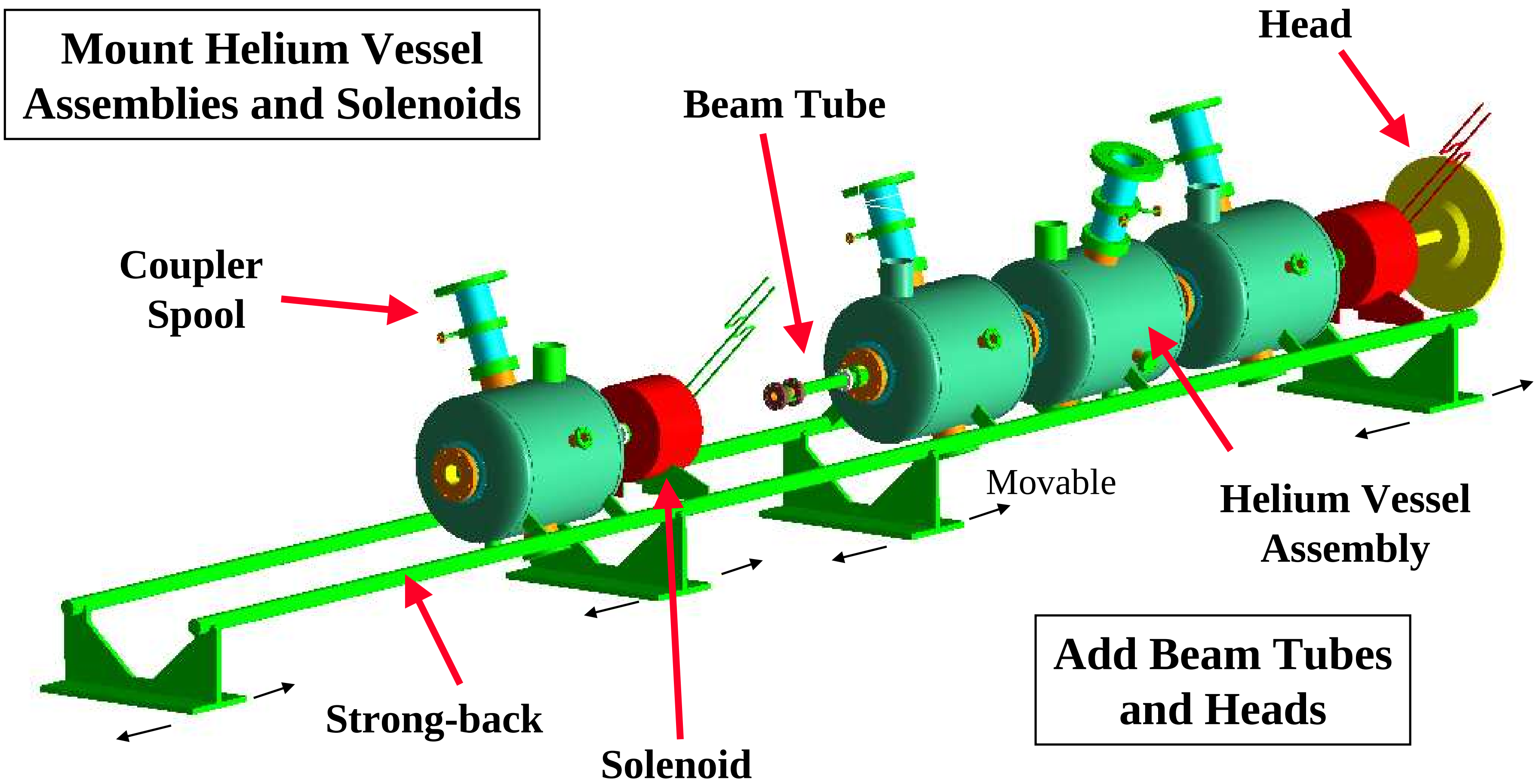
Spoke Cavity Cryomodule - Flowsheet



Spoke Cavity Cryomodule Clean Room Assembly

- **Known - relative positions of beam center line, coupler inner flange and foot pads.**
- **Helium vessel assemblies (cavity/coupler/helium vessel)**
  - **Are mounted on pre-aligned strong-back**
  - **Fiducials are added to outer coupler flanges (for relating position of beam tube centerline to coupler outer flange)**
  - **Beam tubes are installed.**
  - **Temporarily locked-down to strong-back**
- **Solenoid magnet assemblies**
  - **Are mounted on the strong-back.**
  - **Beam tubes are installed (cavity to solenoid, solenoid to ambient).**
- **Transfer alignment data to fiducials on outer coupler flanges**
- **Final lock-down to strong-back**

Spoke Cavity Cryomodule Clean Room Assembly - Figure



Spoke Cavity Module Final Cold Mass Assembly

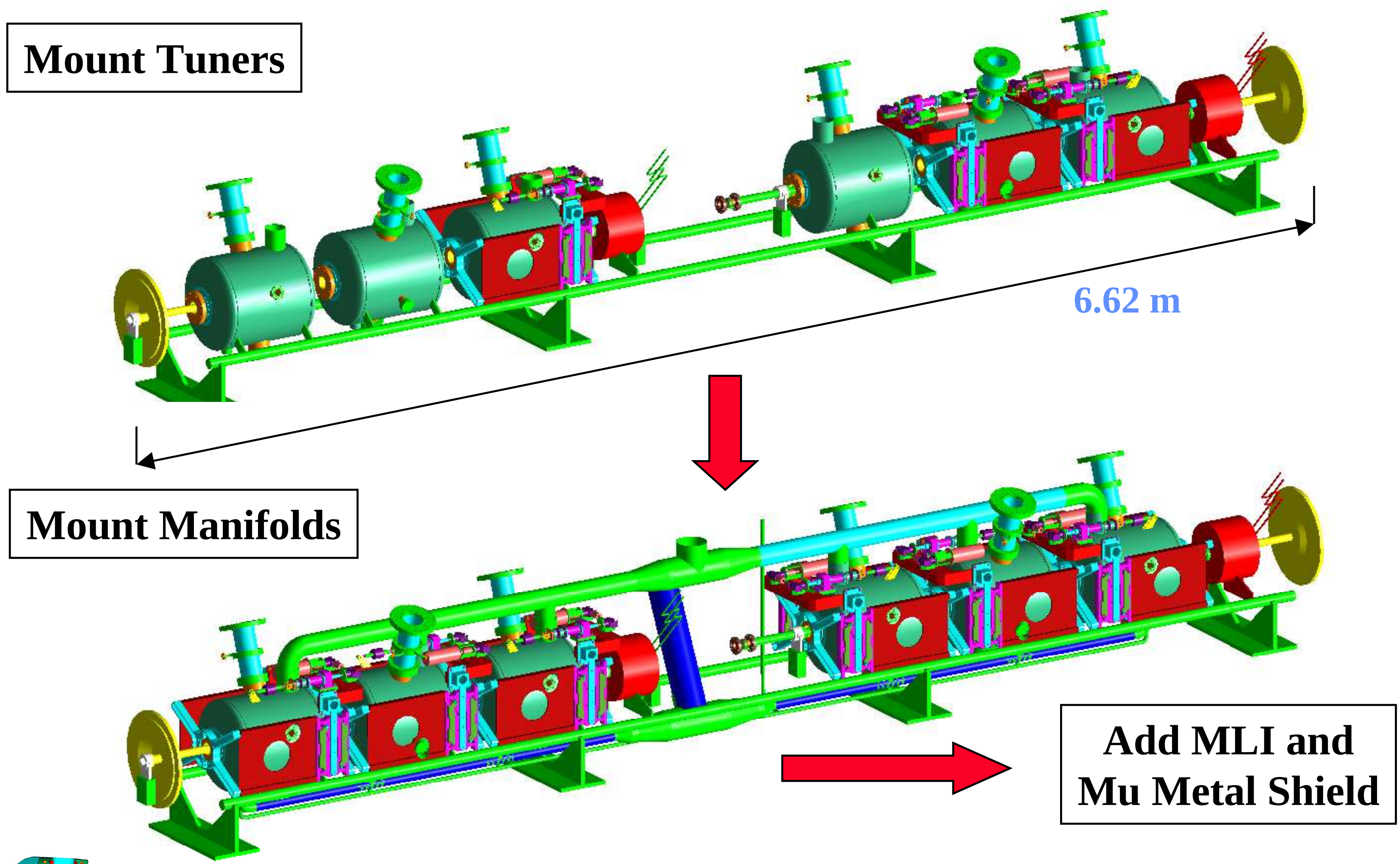
- **Remainder of assembly performed outside the clean room**

- **Mount tuner assemblies**
  - **Tuner - Same as the APT Tuner**
  - **Cold Motor - Saclay-TESLA-SNS Pedigree**
  - **Piezoelectric actuator**
    - » **Allows for cavity detuning in < 300 msec.**

- **Mount manifolds**
  - **2” tube supply, 4” tube return, 1/2” tube cooldown supply**

- **Add multilayer insulation blanket (MLI - 15 layers) and Mu metal shield (0.040” thick)**

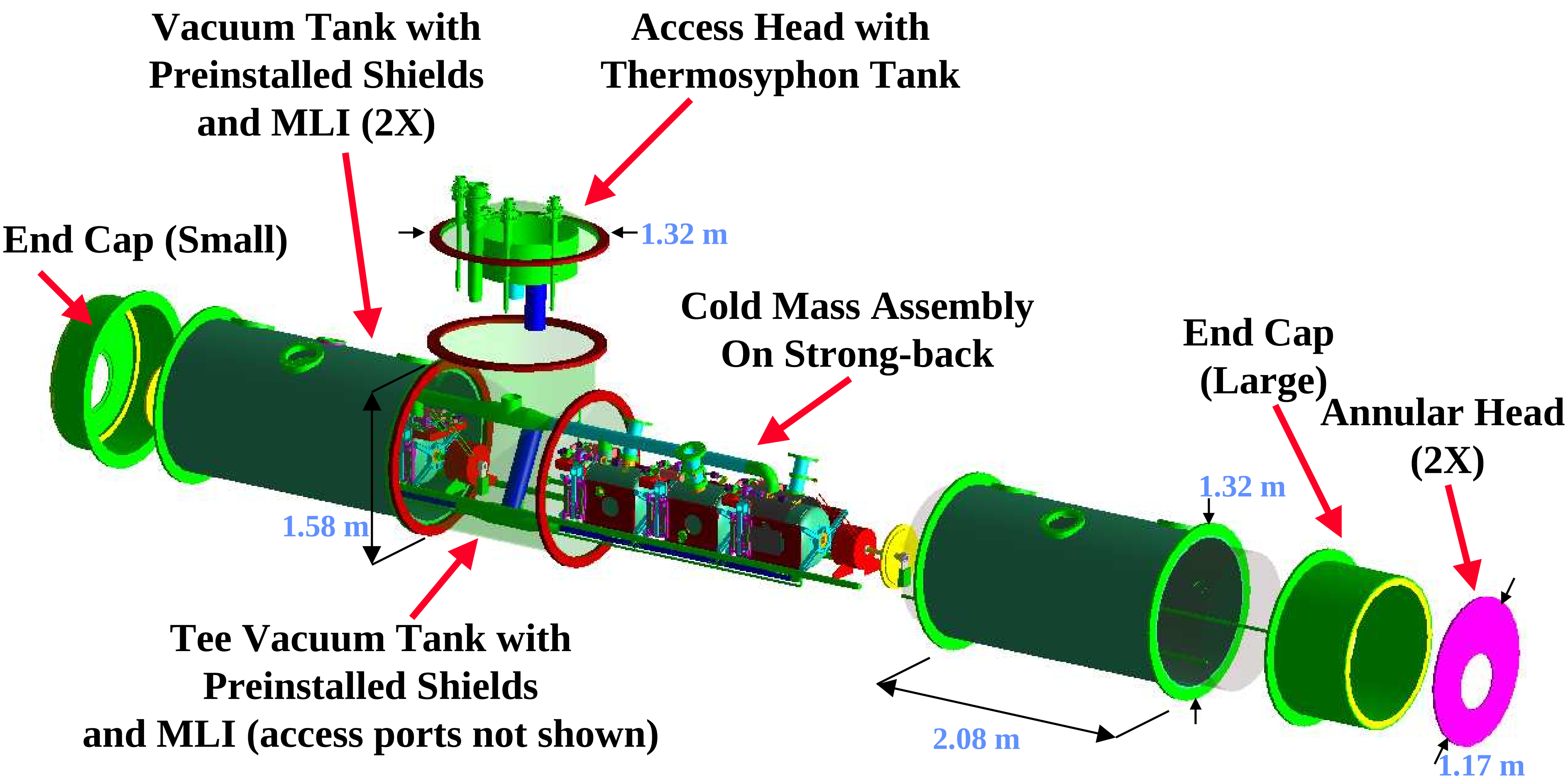
Spoke Cavity Module Final Cold Mass Assembly - Figure



Spoke Cavity Module Final Assembly

- **Insert cold mass assembly into prefabricated Tee section**
  - **Tee thermal shield (Cu), magnetic shield (Mu metal - 0.040") & MLI blankets (4 @ 15 layers ea.) preinstalled.**
- **Mount vacuum vessel cylinders to Tee section**
  - **Thermal shield, MLI blankets, magnetic shield preinstalled (similar to CEBAF's approach).**
  - **Thermal shield & MLI blanket bridges made.**
- **Mate couplers/solenoids to vacuum vessel**
  - **Couplers are only mechanical support for helium vessel assemblies**
  - **Solenoids use compression post support**
    - » **Similar posts used by SSC, RHIC, LHC**
- **Remove strong-back**
- **Install current lead feedthroughs**
- **Install Tee-section head/internals - make pipe connections**
- **Install end caps**

Spoke Cavity Cryomodule Final Assembly - Figure



Spoke Cavity Cryomodule Summary

- **Adopted concepts and components from previous programs - <u>minimize risk</u>.**
- **Thermosyphon cooling - improves thermal performance.**
- **Coupler supported cavities**
  - **simplifies assembly,**
  - **minimizes thermal shorts, magnetic fringe fields, and**
  - **reduces part count.**
- **Axial insertion**
  - **minimizes clean room time and**
  - **simplifies assembly.**
- **Similar work has been done by industry.**

Back-up Slides

Section 4 (Largest) Solenoid Magnet Dimensions and Parameters

- **Electrical Parameters**
  - Current – 20 A
  - Inductance – 280 H
  - Power Supply Voltage – 20 V
  - Field @ Centerline – 6 T
  - Field 6.5 cm from end of windings - < 0.1 T
  - Charge time – 280 sec.
  - Stored Energy – 56 kJ
- **Physical Parameters**
  - Cold Bore Diameter – 11 cm
  - Active Length – 30 cm
  - Diameter of Windings – 15.3 cm
- **Leads – Conduction Cooled**
  - Intercepted at the shield temperature

Largest Solenoid Magnet Dimensions and Parameters

- **Cooling (Steady State and Cooldown) – Supercritical He @ 4.5 K, 4 atm.**
- **Quench**
  - **Magnet goes normal in ~ ½ second.**
  - **Temperature reaches ~ 185 K**
  - **Boiloff at 4.5 K sat. ~ 23 L**
  - **Recovery Time – System Dependent**
  - **Note – Segmenting or some other approach will be necessary to minimize internal voltages generated during quench.**

Spoke Cavity Coupler Heat Loads*
(100 milliamps - No Margin)

	RF On	RF On	RF On	RF Off
Inner Conductor Cooling Temp.	300 K	300 K	300 K	300 K
Tunnel/Compressor Water Temp.	300 K	300 K	310 K	300 K
Intercept Temp.	40 K	50 K	40 K	40 K
4.5 K Heat Load	3.8 W	4.7 W	3.8 W	3.3 W
Intercept Heat Load	20.6 W	19.2 W	21.7 W	20.5 W
Wall Power	1436 W	1549 W	1512 W	1303 W

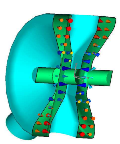
*Waynert, Joe, *Thermal Analysis on ADTF Spoke Cavity Power Coupler*, ESA-EPE:01-075, March 30, 2001.

Spoke Cavity Cryomodule Preliminary 4.5 K Heat Loads (100 milliamps - no margin)

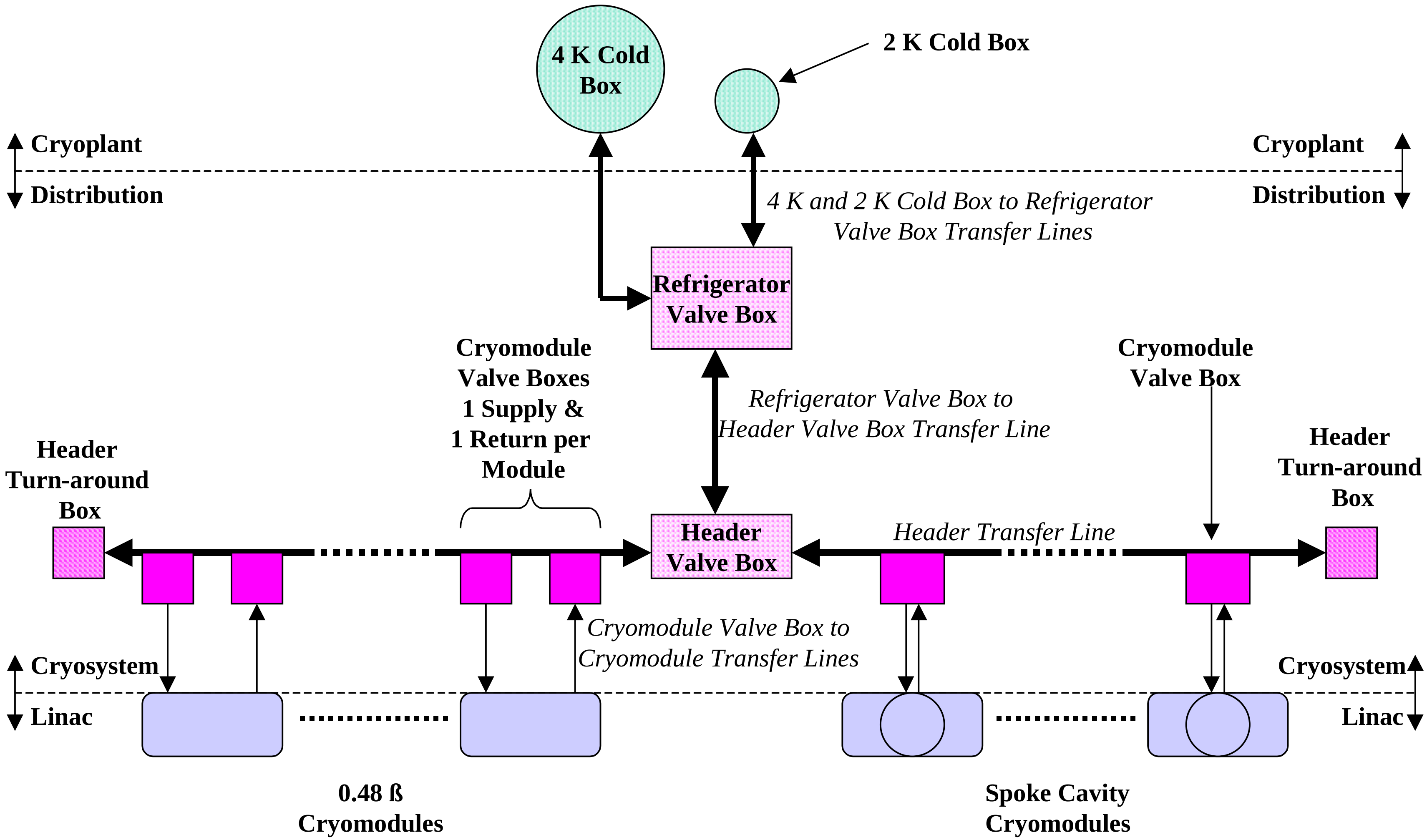
	β = 0.175			β = 0.2			β = 0.34		
Unit	**# Units**	**H.L/Unit**	**Tot. H.L.**	**# Units**	**H.L/Unit**	**Tot. H.L.**	**# Units**	**H.L/Unit**	**Tot.H.L.**
Cavity (Krawczyk)	4	2.85	11.4	6	8.37	50.22	6	14.64	87.84
Couplers (Waynert)	4	4	16	6	4	24	6	4	24
Beam Tube (Waynert)	2	0.7	1.4	2	0.7	1.4	2	0.7	1.4
Current Lead Pair - 20 A (Weisend)	2	0.4	0.8	2	0.4	0.8	2	0.4	0.8
Radiation (0.02 W/m^2)	17.23	0.02	0.34	22.89	0.02	0.46	25.84	0.02	0.52
Small Male & Female Bayonets	3	0.41	1.23	3	0.41	1.23	3	0.41	1.23
Large Male & Female Bayonet	1	1.7	1.7	1	1.7	1.7	1	1.7	1.7
Valves (used APT Value for JT)	4	0.25	1	4	0.25	1	4	0.25	1
Relief Lines (small)	2	0.024	0.047	2	0.024	0.047	2	0.024	0.047
Relief Lines (large)	1	0.14	0.14	1	0.14	0.14	1	0.14	0.14
Cables (used APT value)	1	0.7	0.7	1	0.7	0.7	1	0.7	0.7
Solenoid Supports (CERN LHC Post)	2	1	2	2	1	2	2	1	2
Strong-back Supports (CERN LHC Post)	4	1	4	4	1	4	4	1	4
HOMs ($\leq$ 2 W TBD - Krawczyk)	4	2	8	4	2	8	4	2	8
Total 4.5 K Heat Loads			**48.76**			**95.70**			**133.38**

Spoke Cavity Cryomodule Preliminary Shield Heat Loads (100 milliamps - no margin)

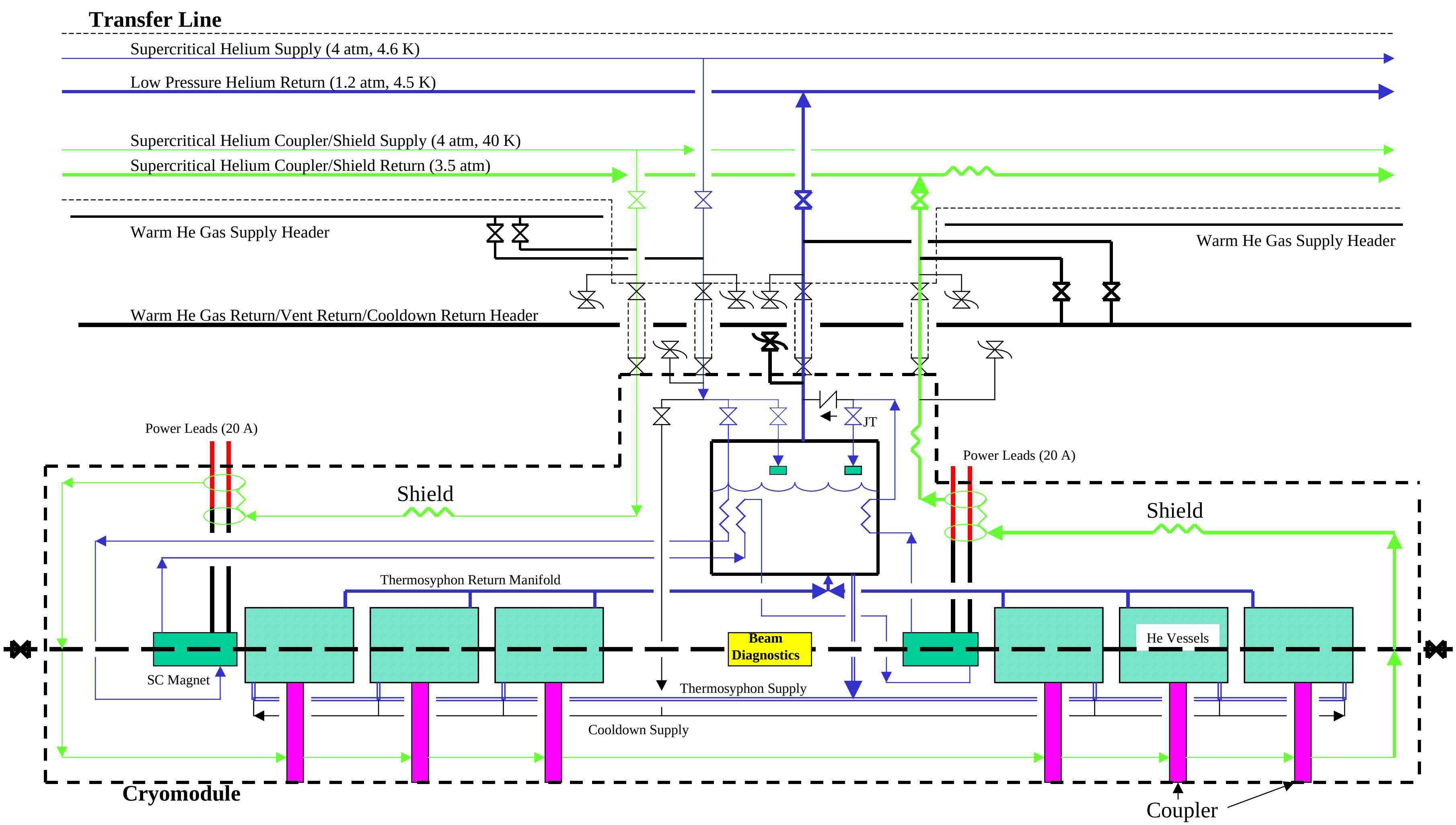
	β = 0.175			β = 0.2			β = 0.34		
Unit	**# Units**	**H.L/Unit**	**Tot. H.L.**	**# Units**	**H.L/Unit**	**Tot. H.L.**	**# Units**	**H.L/Unit**	**Tot.H.L.**
Cavity (Krawczyk)	4	0	0	6	0	0	6	0	0
Couplers (Waynert)	4	20.6	82.4	6	20.6	123.6	6	20.6	123.6
Beam Tube (Waynert)	2	1.47	2.94	2	1.47	2.94	2	1.47	2.94
Current Lead Pair - 20 A (Weisend)	2	1.6	3.2	2	1.6	3.2	2	1.6	3.2
Radiation (1 W/mA^2)	17.23	1.00	17.23	22.89	1.00	22.89	25.84	1.00	25.84
Small Male & Female Bayonets	3	0.75	2.25	3	0.75	2.25	3	0.75	2.25
Large Male & Female Bayonet	1	2.56	2.56	1	2.56	2.56	1	2.56	2.56
Valves (used APT Value for JT)	4	2.5	10	4	2.5	10	4	2.5	10
Relief Lines (small)	2	0.425	0.850	2	0.425	0.850	2	0.425	0.850
Relief Lines (large)	1	2.551	2.551	1	2.551	2.551	1	2.551	2.551
Cables (used APT value)	1	2	2	1	2	2	1	2	2
Solenoid Supports (CERN LHC Post)	2	8	16	2	8	16	2	8	16
Strong-back Supports (CERN LHC Post)	4	8	32	4	8	32	4	8	32
HOMs	4	0	0	4	0	0	4	0	0
Total Shield Heat Load			**173.98**			**220.84**			**223.79**



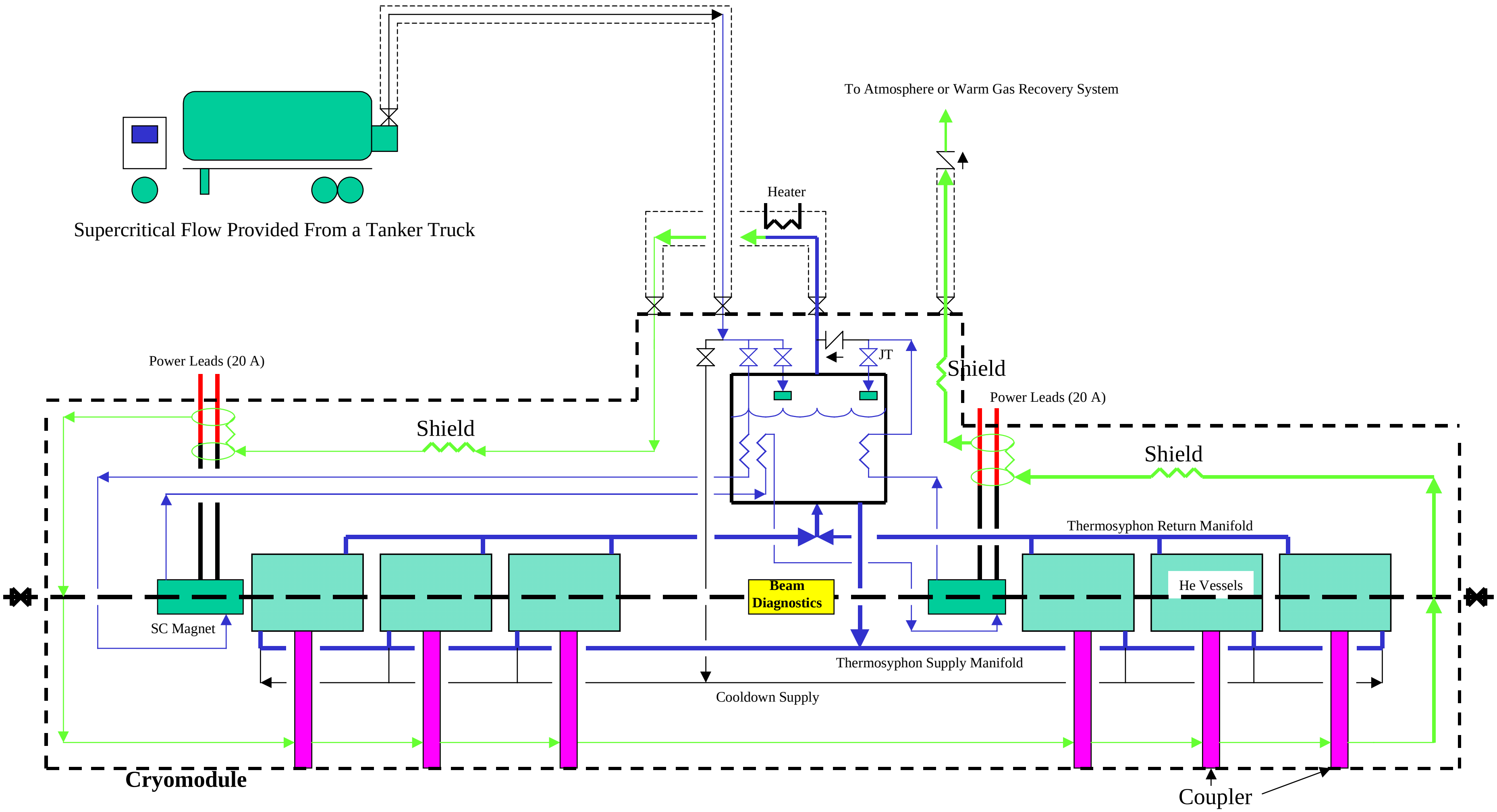
LEL Refrigeration - Conceptual Layout - APT
Type ß = 0.48 Cryomodule



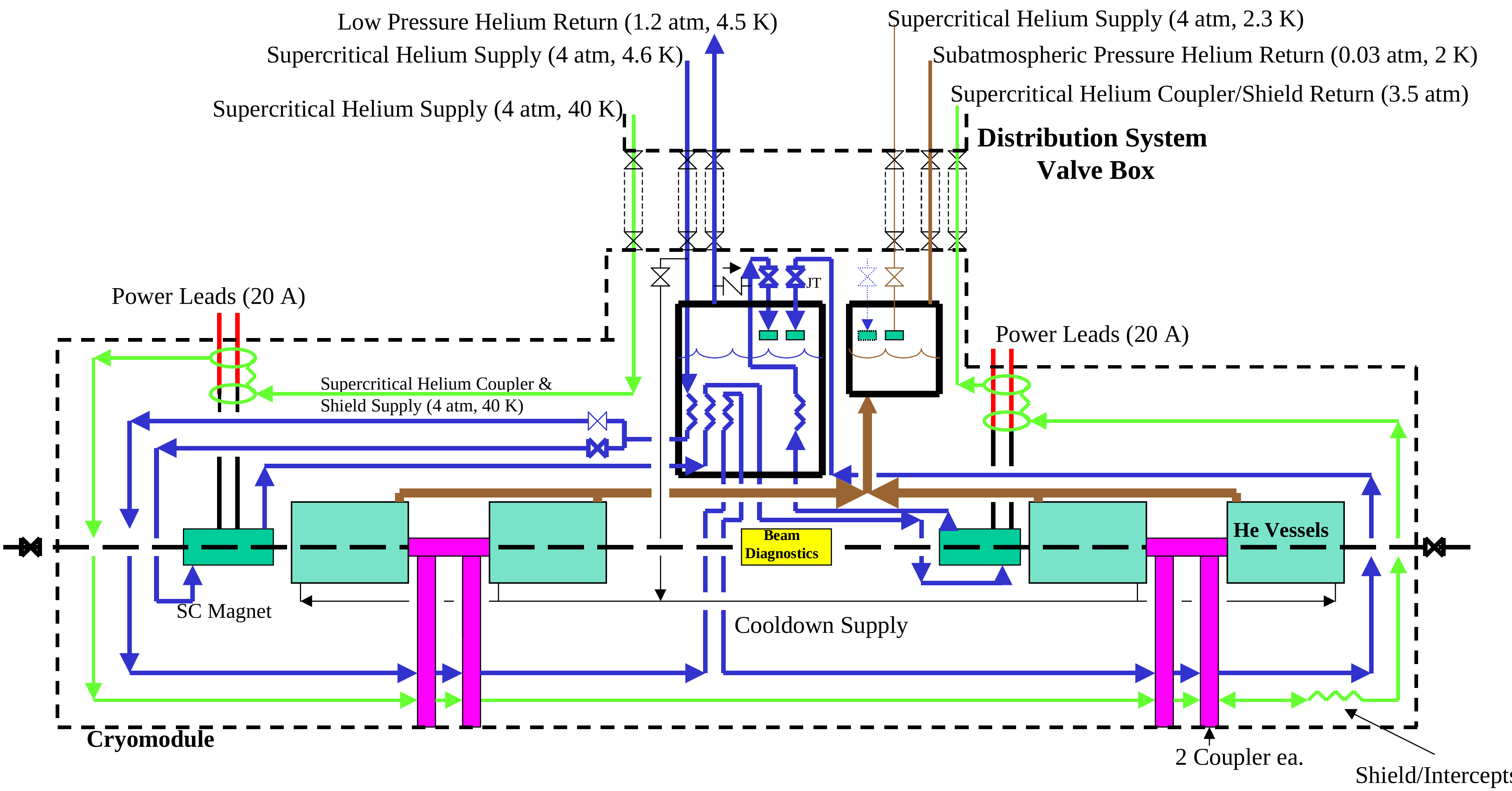
Spoke Cavity Cryomodule Interface to Distribution System Flowsheet



Spoke Cavity Module Test Flowsheet



ß = 0.48 Cryomodule - Flowsheet



Discussion on "ADTF Spoke Cavity Cryomodule Concept" by J. Patrick Kelley

The ADTF cryomodule design incorporated focusing solenoids inside the cryomodule. Bath-cooling of the solenoids is not considered due to expected pressure pulses in the system, if the coil would quench.

The heat loads due to the power coupler are 3.8 W into 4.5 K and approximately 20 W into the 40 K intercept. These numbers are for a preliminary accelerator design with a gradient of 5 MV/m.

The design concept uses the power coupler outer conductor as part of the support structure. Concern about low-frequency mechanical resonances transferred to the cavity were expressed. Kelley responded that the setup is very stiff, cryo-feeds use flexible connections to decouple them from the system and further stiffening and/or damping can be incorporated, if needed.

The final question addressed a possible use of 2K and the related re-design of this cryomodule. Kelley answered that the top-part of the cryomodule due to the changes in the distribution system would be the only part seeing major changes, also an additional reservoir would have to be added. Inside the cryostat the only change he could see would be an additional intercept at the niobium to stainless transition of the outer conductor of the power coupler. The cryo-vessel itself and the helium vessel would not need any changes.

Alternate Concepts

Ken Shepard: "*Spokes for Pulsed Operation*"
(Discussion)
Tsuyoshi Tajima: "*Consideration of 2K Operation*"
(Abstract | Viewgraphs | Discussion)
Alberto Facco: "*Development of a 352 MHz, Low-beta Superconducting Reentrant Cavity at LNL*"
(Abstract | Viewgraphs | Discussion)
Andreas Sauer: "*Multi-Cell SC CH-Cavity*"
(Abstract | Viewgraphs | Discussion)
Bob Garnett: "*RF-Focused Spoke Resonator*"
(Abstract | Viewgraphs | Discussion)

Discussion on "High β Spokes/Pulsed Operation" by Ken Shepard

This session was a pure discussion session. It focused on Lorentz Force Effects (Lorentz Force Coefficient (LFC), Lorentz Force Detuning (LFD)). Shepard provided the information that for the ANL/RIA spokes the coefficient even for an unconstrained cavity was only a few Hz/(MV/m)^2. Thus they never considered this a problem for their operation. But the results show that spokes are suitable candidates for 4K pulsed operation. Delayen clarified, that the static LFC is not the point of the story. For pulsed operation it needs to be understood, what mechanical modes exist at the harmonics of the pulse frequency. The correlation between the static LFC and the related issues for pulsed operation are not understood at all.

It is difficult to measure LF effects in a vertical test, as the cavity bandwidth is important. Only a loaded resonator has a bandwidth that allows to measure the high frequencies (at least a few kHz) that are dangerous in operation. Instead of beam loading, loading by a 2nd coupler could be used. Success is still not clear as the coupling might not be strong enough (Q_x 10^4 - 10^5) to get to substantial field levels in the rise times needed (a few 100 µsec to 1 msec).

When discussing potential experiments, it turned out that ANL could do pulsed tests on existing hardware with a 1 msec rise time (they have 7 kW of power and need to store around 80 mJ of energy) up to field levels of about 3-4 MV/m. This could give some information on mechanical modes that could be excited.

Pagani contributed details on the excitations that need to be considered. He thinks that experiments by ANL, where they do an amplitude modulation with high frequency is useful, but not sufficient. What is needed, is an excitation with cavity deformations that resemble the LFD effect. He reported numerical experiments, where they did determine the 3D deformations due to Lorentz Forces and excited 3D models of cavities with sinusoidal variations of these deformations. A frequency sweep will show the electromagnetic oscillations (using Slater's Theorem) and the excitation of mechanical modes (with a mechanical modeler). He also mentioned that the pulse shape (giving the relative contributions from different frequencies) is of less importance, than the repetition pattern of the pulse.

He further elaborated on the numerical complexity of the task. Low frequency mechanical modes (a few 10s or 100s of Hz) are excited through harmonics of deformations at several kHz. The electromagnetic effects are driven by marginal structure deformations in the nm-range.

Shepard summarized the issue as: "We need to characterize the transfer function of the cavity-auxiliary system to as high a frequency as possible". Pagani mentioned that Kako from KEK has done very useful work on this topic. Delayen emphasized the importance of the characterization of the "real" system including external forces, auxiliary components, ...

Pagani re-iterated that the transfer function cannot be obtained by a white noise excitation of the cavity system, as the deformations are not the LFD triggered deformations.

In summary, spoke resonators are promising candidates for pulsed operation with little LFD issues. Useful measurements should be developed in a coordinated effort.

Consideration of 2K Operation

T. Tajima, LANL

The difference between 2 K and 4 K operations in terms of the cavity performance will be discussed. We have experienced with some 700-MHz, 5-cell, beta=0.64 elliptical cavities that the maximum accelerating gradient was much higher at 2 K than that at 4 K. With the tests with the ANL 340-MHz, beta=0.29, 2-gap spoke cavity and LANL 350-MHz, beta=0.175, 2-gap spoke cavity, the maximum gradient at 4 K and 2 K have been the same so far. The difference of Q_0 will also be discussed as well as a crude discussion of the difference in installation and operational costs.

Considerations of 2 K Operations

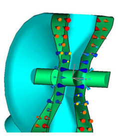
Tsuyoshi Tajima
LANL

Workshop on the Advanced Design of Spoke Resonators

Los Alamos, NM, USA
October 7 and 8, 2002

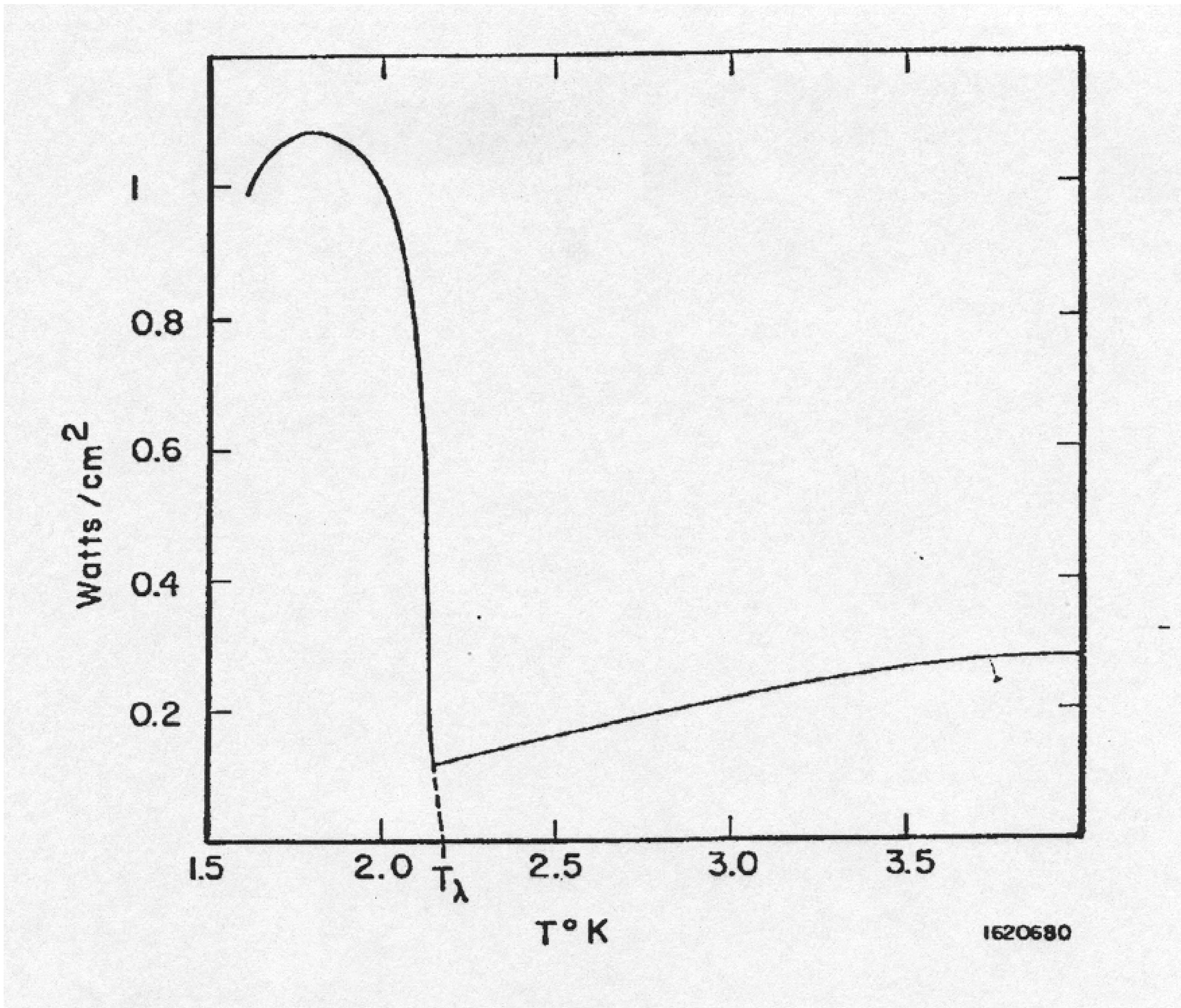
What are the differences between 4 K and 2 K?

- Thermal conductivity of LHe at 2 K is much greater than at 4 K
  - Thermal conductivity of saturated 4 K liquid helium is 1.87E-2 W/mK.
  - Thermal conductivity of 2 K superfluid helium is 1.2E5/q^2 W/mK. (q is heat flux in W/cm^2).
- Cavity surface resistance Rs gets lower with lower temperatures, i.e., BCS resistance decreases exponentially with temperature.



Film boiling limit vs. bath temperature

(H. Padamsee, “Heat transfer and models for beakdown,” CLNS 80/469, July 1980)



The Cavity Surface Resistance, R_s

$$R_s = R_{BCS} + R_{residual}$$

$$R_{BCS} = A \cdot \frac{f^2}{T} \cdot \exp\left(-\frac{\Delta}{k_B T_c} \cdot \frac{T_c}{T} \right)$$

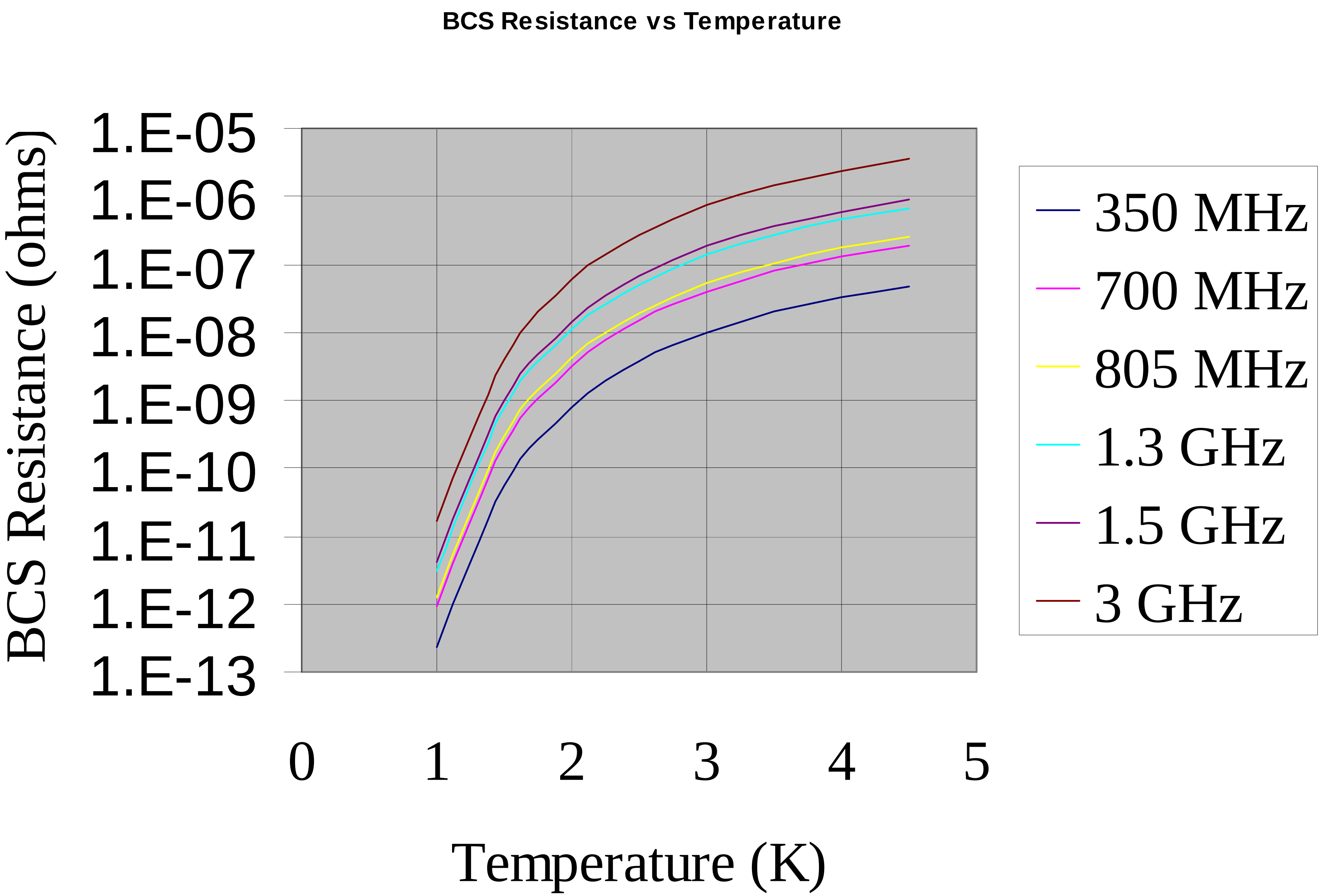
f: Cavity frequency
T: Operation temp.
Δ: Energy gap
T_c: Transition temp,
9.25 K for Nb.

$$R_{BCS}(\mathrm{ohm}) = 2\times10^{-4} \frac{1}{T} \left(\frac{f\,[\mathrm{GHz}]}{1.5} \right)^2 \exp\left(-\frac{17.67}{T} \right)$$

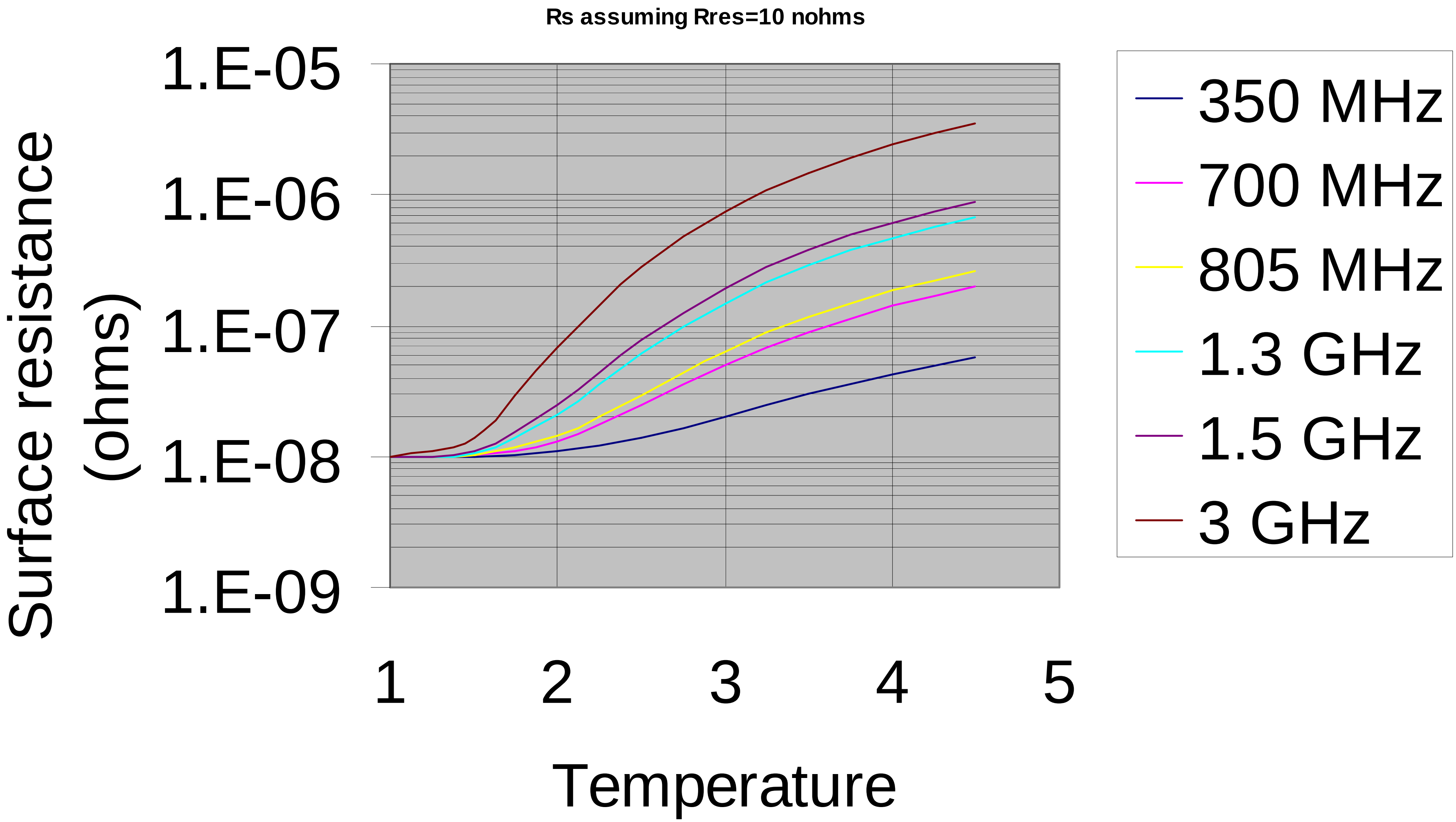
$$R_{res} = R_{res}(H_{rf}) + R_{fl}(H_{rf}, H_{ext}, T)$$

R_{res} = 1 ~ 10 nohms with well prepared surface

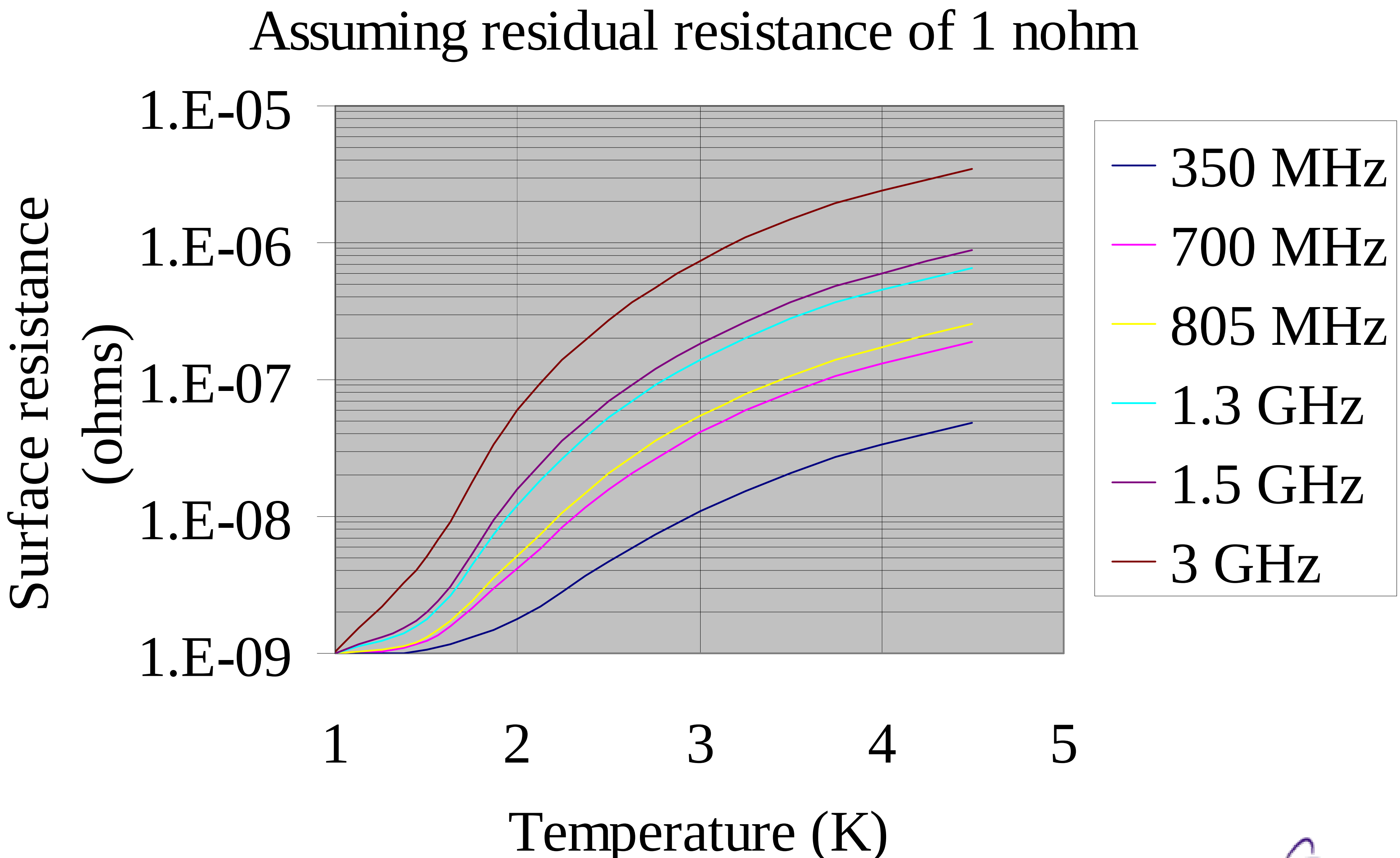
BCS Resistance vs. Temperature



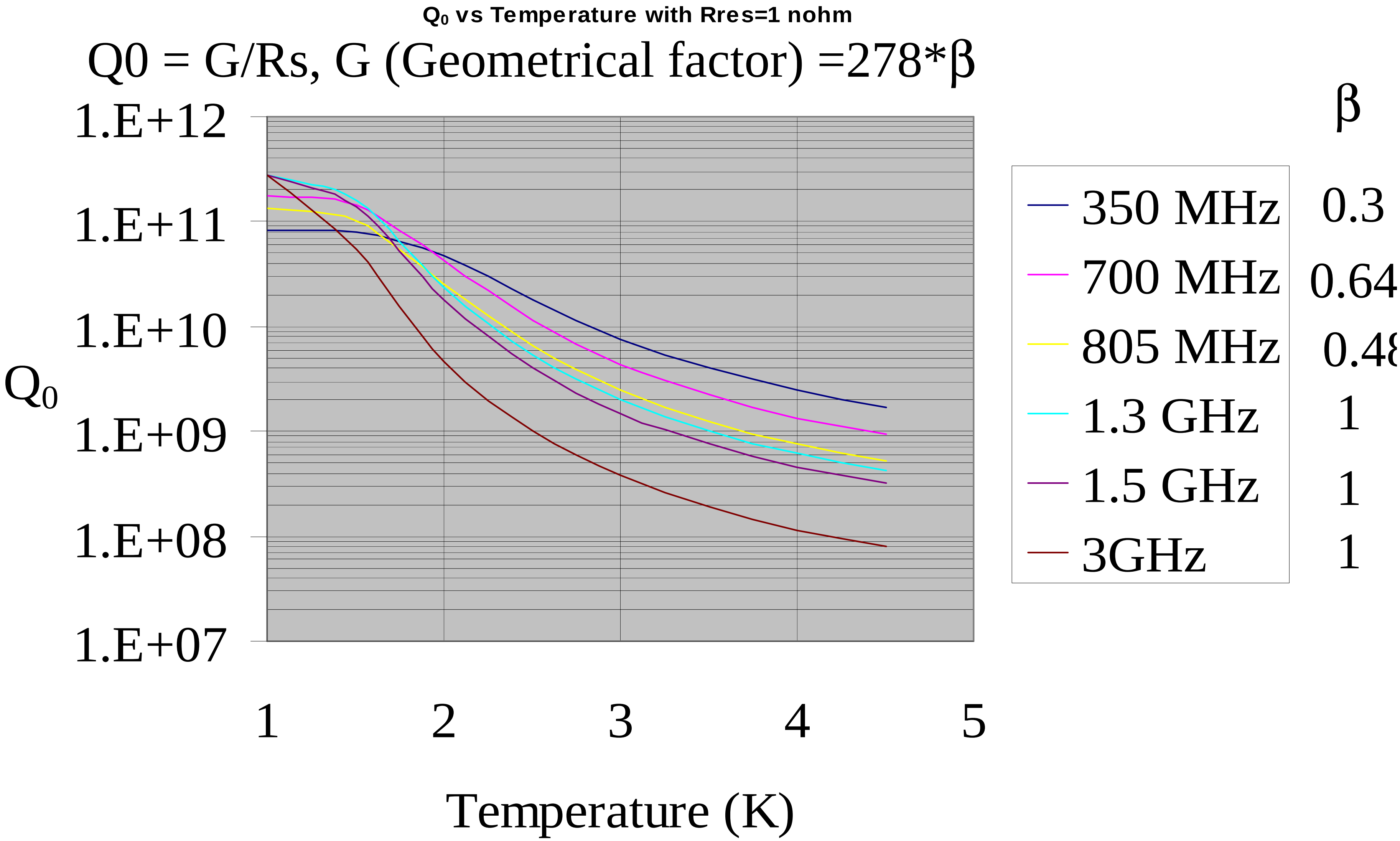
Surface Resistance with R_{res}= 10 nohms

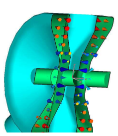


Surface resistance with R_{res}= 1 nohm

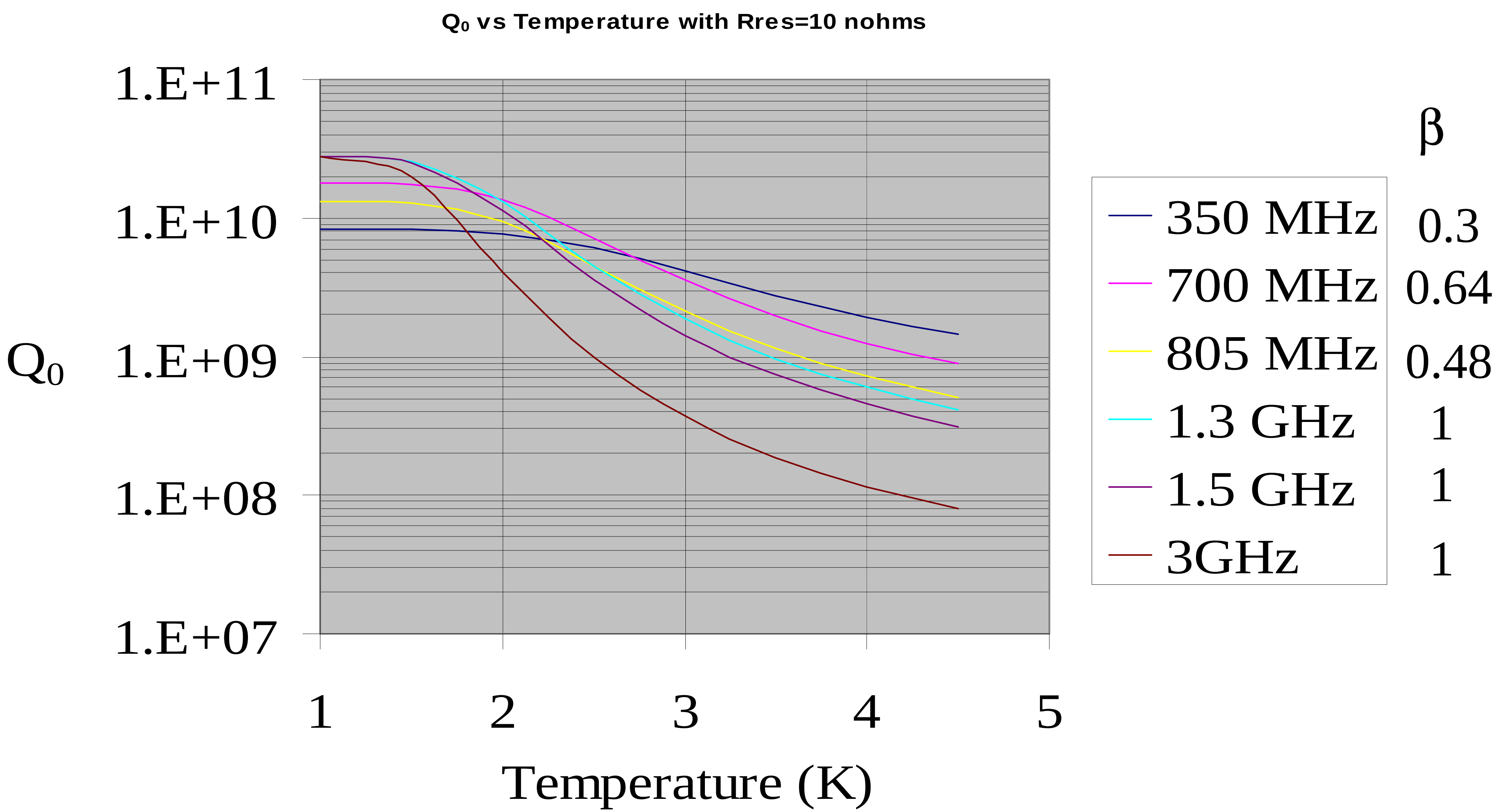


Q_0 vs. Temperature with R_{res} = 1 nohm

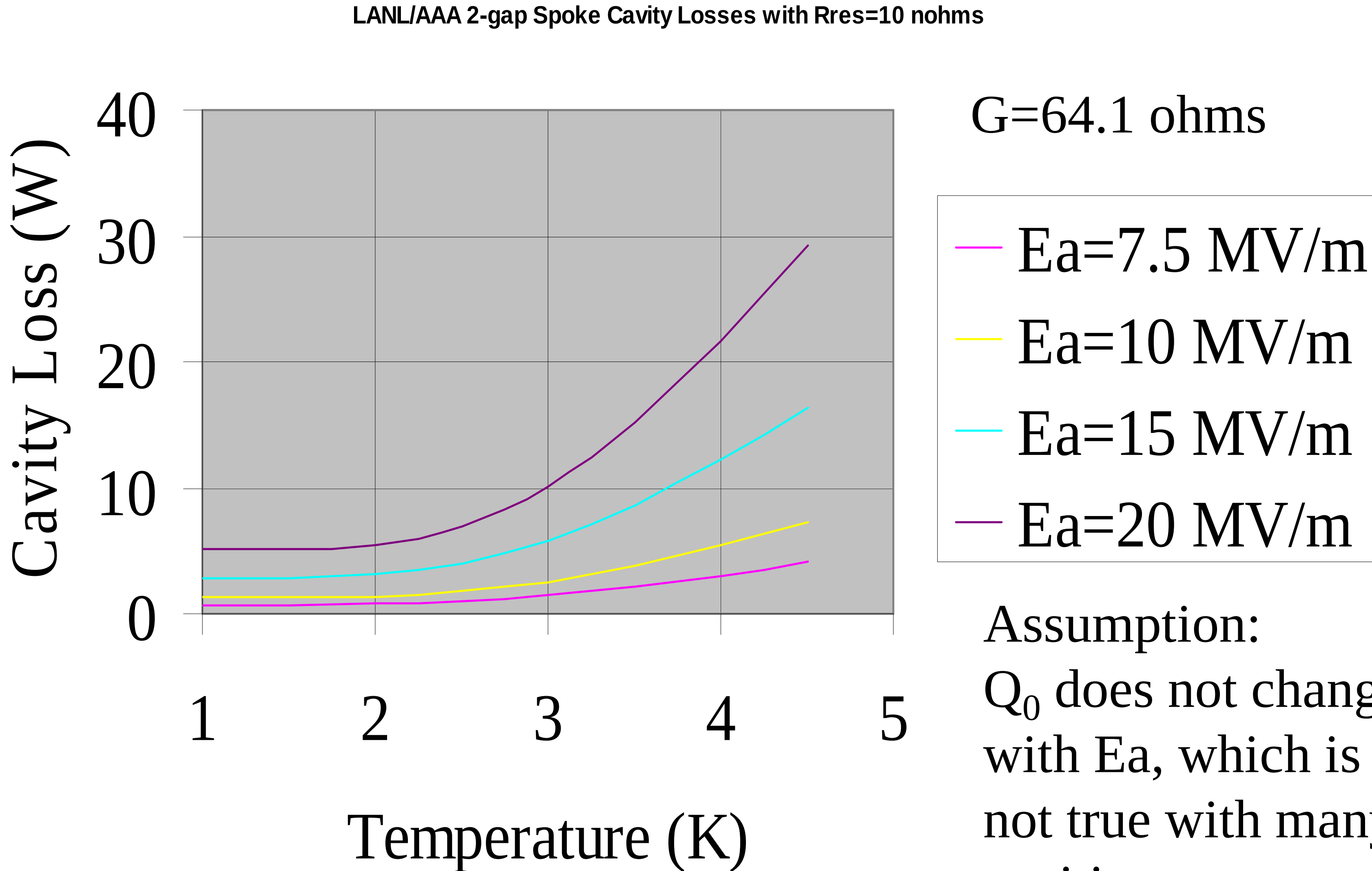




Q_0 vs. Temperature with R_{res} = 10 nohms



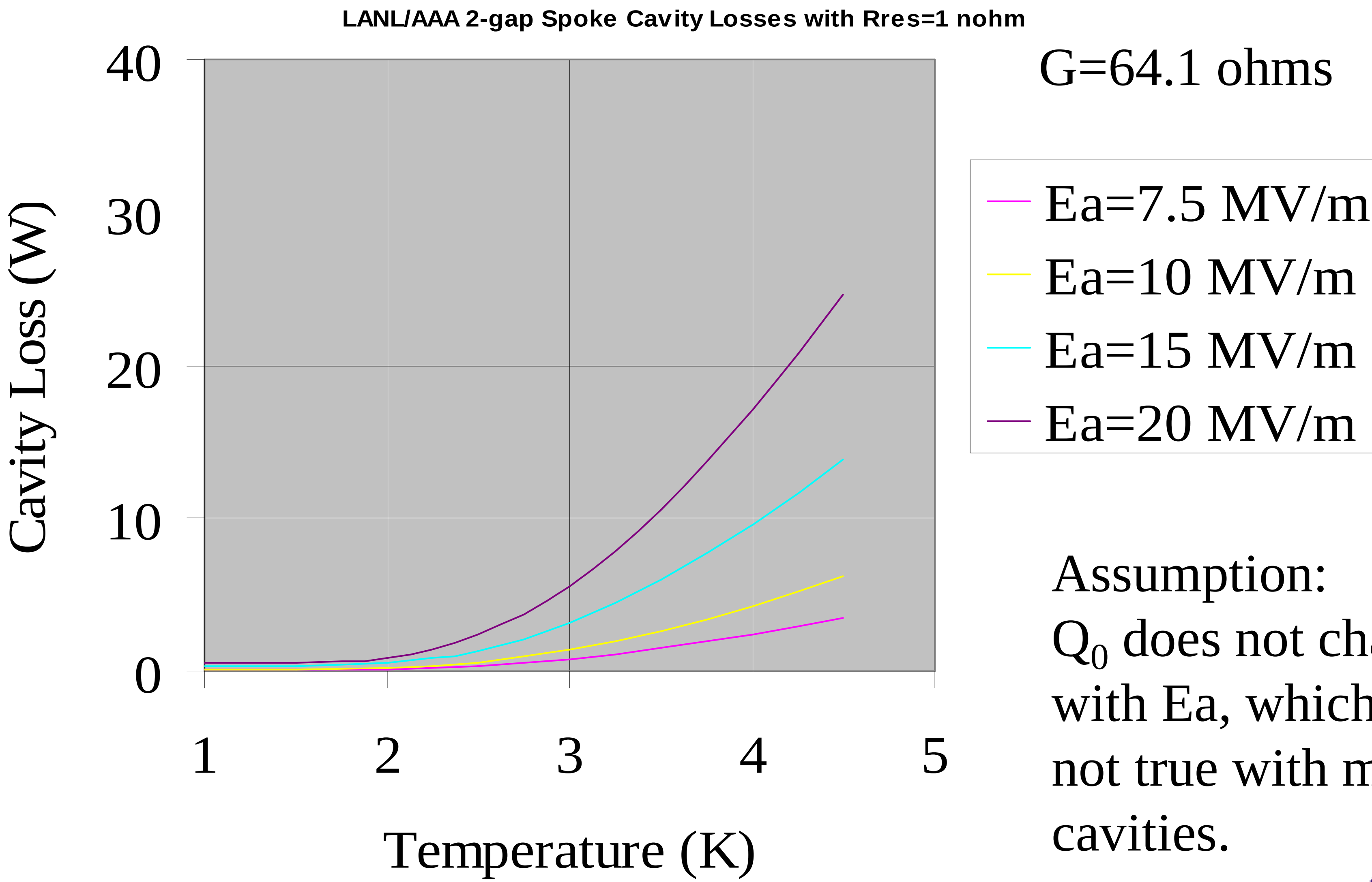
Cavity Loss of LANL/AAA 2-Gap Spoke, R_{res} = 10 nohms



G=64.1 ohms

Assumption:
Q_0 does not change with Ea, which is not true with many cavities.

Cavity Loss of LANL/AAA 2-Gap Spoke, R_{res} = 1 nohm



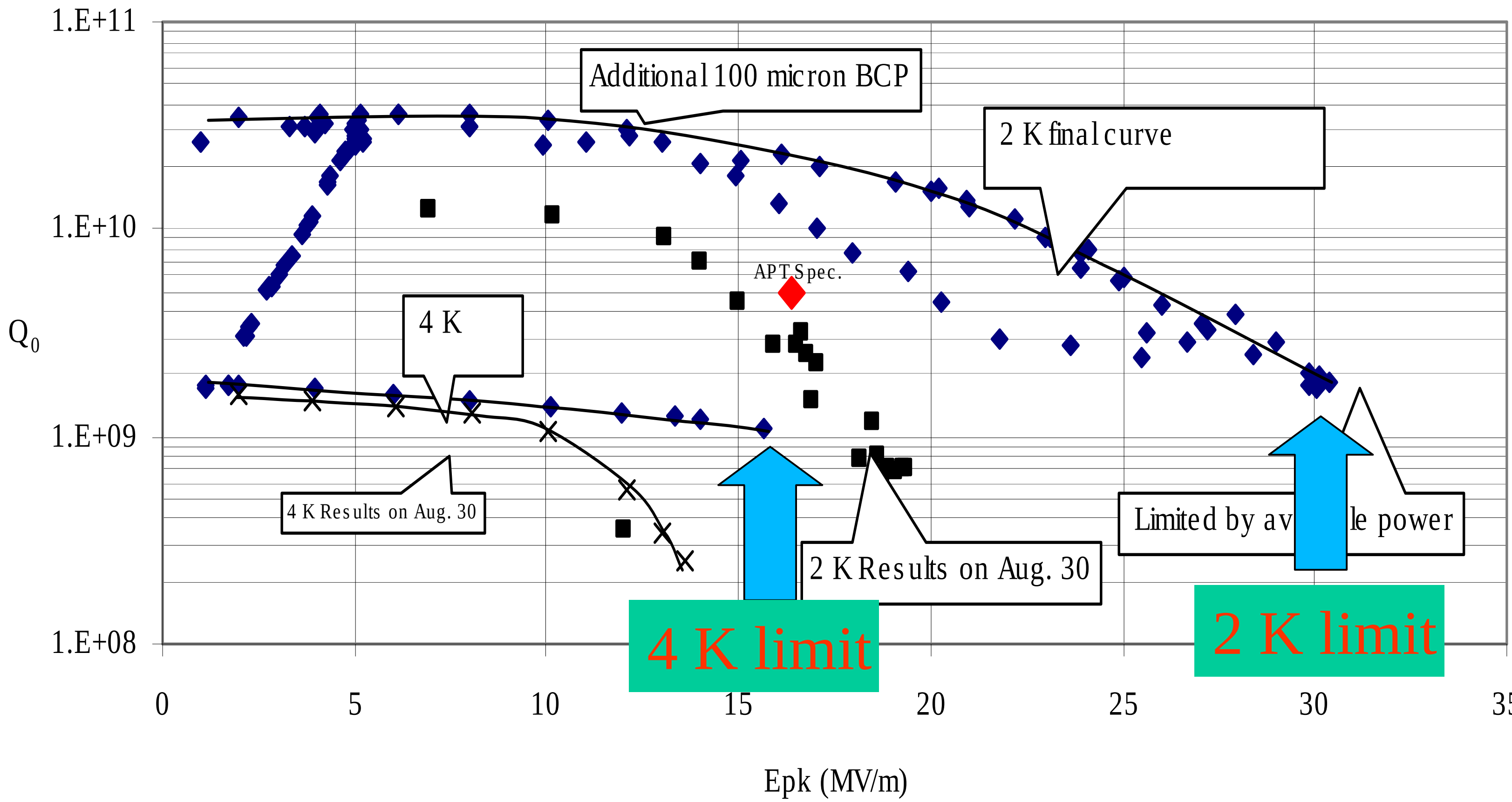
G=64.1 ohms

Assumption:
Q_0 does not change with Ea, which is not true with many cavities.

An Experience with LANL/APT 700-MHz β=0.64 Elliptical Cavity

LANL Cavity on 1-18-01 with the data on 8-30-00

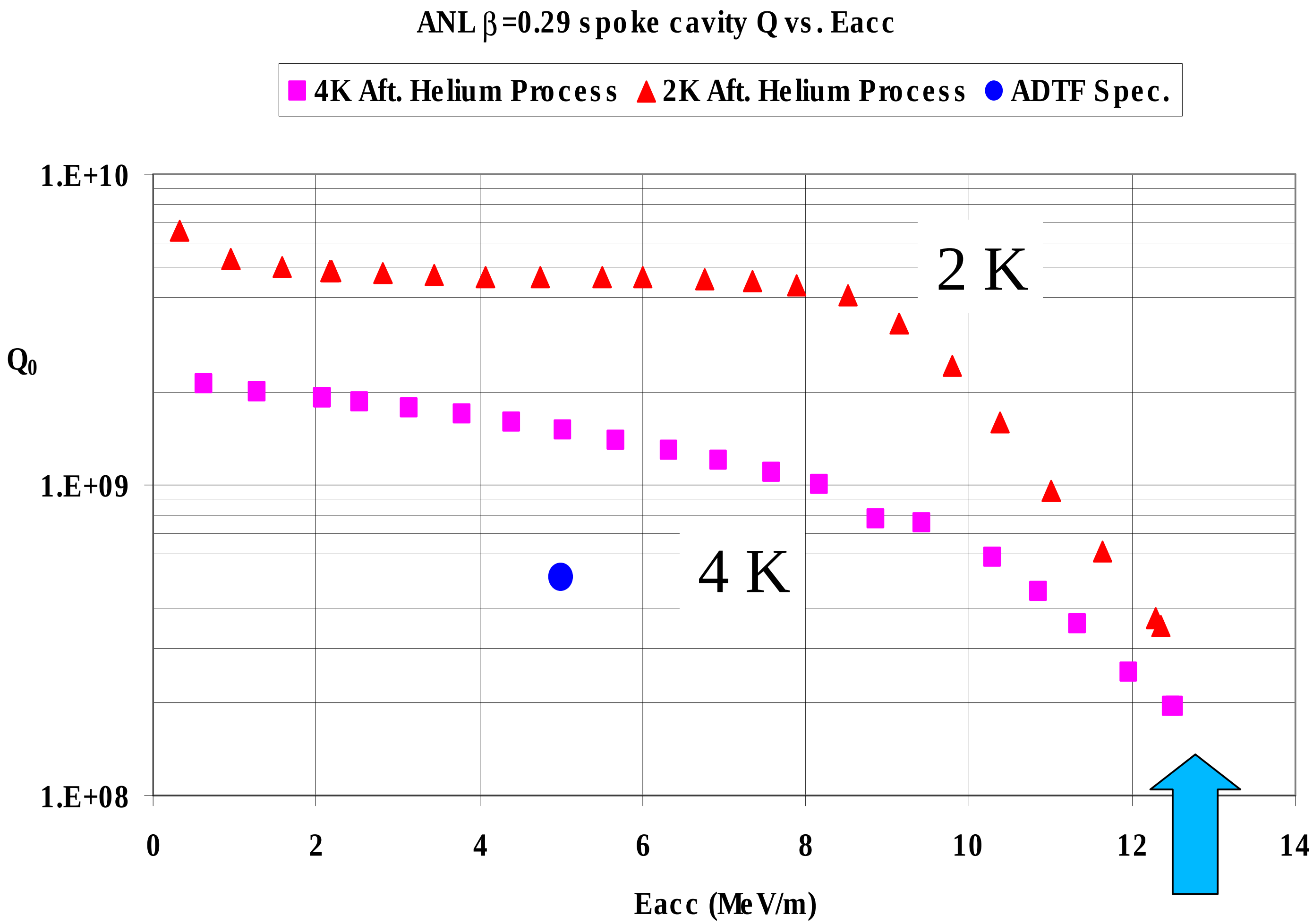
There is a defect on the equator weld of middle cell and limited by quencl



•2 K is not always better than 4 K.

Los Alamos NATIONAL LABORATORY

An Experience with ANL β=0.29, 340-MHz, 2-Gap Spoke Cavity



4 K and 2 K limits are the same

How About Costs of a Cryogenic Plant at 4.5 K and 2 K?

According to H. Safa's paper in LINAC98 conference,

$$\boldsymbol{C}_{\boldsymbol{captital}}(\$) = 3000\left(3 + \frac{4.5}{\mathrm{T}}\right)\left(\frac{\eta_{4.5\boldsymbol{K}}}{\eta}\mathrm{R}\right)^{0.7}$$

$$\boldsymbol{C}_{\boldsymbol{operation}}(\$/\,\boldsymbol{year}) \approx 0.35 \times \mathrm{P}_{\mathrm{AC}} = 0.35\frac{\mathrm{R}}{\eta}$$

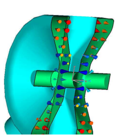
T: operation temperature

R: refrigeration power in W

$\eta_{4.5K}$: overall efficiency at 4.5 K

η: overall efficiency

P_{AC}: AC electric power of the cryogenic plant



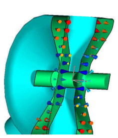
Overall Efficiency of Cryogenic Plant, η

$$\eta = \eta_r \cdot \eta_{Carnot}$$

$$\eta_r = 0.035\,\mathrm{Ln}(\mathrm{R})\tanh\left(\frac{\mathrm{T}}{3}\right)$$

$$\eta_{Carnot} = \frac{\mathrm{T}}{\mathrm{T_a} - \mathrm{T}}$$

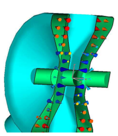
T_a: Room temperature, 310 K is generally taken.



An Example with AAA 600 MeV Nuclear Waste Transmuter

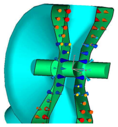
Assumptions:						
Ref. SC Linac Design Parameters,						
Strawman S2 Design 6, R. Garnett, LANSCE-1:01-063						
	β	**f (MHz)**	**Type**	**No. Cavity**	**Ea (MV/m)**	**G (ohms)**
Section 1	0.175	350	2-gap spoke	80	7.5*	64.1
Section 2	0.34	350	3-gap spoke	36	7.5*	94.5*
Section 3	0.48	700	5-cell elliptical	32	7.5*	133*
Section 4	0.64	700	5-cell elliptical	93	7.5*	149

*Modified for simplicity or due to no specific design yet



An Example with AAA 600 MeV Nuclear Waste Transmuter

Costs in M$			
R_{res}=10 nohms			
Operation temperature	**4.5 K**	**4.5K/2K**	**2K**
Capital cost in sections 1 and 2	19.1	19.1	18.7
Capital cost in sections 3 and 4	268	126	126
Total cryogenic loss	24.6 kW	2.13 kW	1.68 kW
Total capital cost	287	145	145
Total operational cost per year	1.85	0.631	0.625
R_{res}=1 nohm			
Operation temperature	**4.5 K**	**4.5K/2K**	**2K**
Capital cost in sections 1 and 2	16.9	16.9	5.32
Capital cost in sections 3 and 4	259	56.4	56.4
Total cryogenic loss	23.4 kW	0.964 kW	0.516 kW
Total capital cost	276	73.3	61.7
Total operational cost per year	1.77	0.269	0.228



Action Items for Further Study

- **Collect more data on the difference of gradient limitation at 4 K and 2 K**
- **Analyze the loss mechanisms and classify the situations where 2 K operation is advantageous.**
- **Cost analyses of cryogenic plant including static losses, margins and other items.**
- **Analyze further the benefits of 2 K only system as compared to 4.5K/2K system.**
- **How about replacing β=0.48 section with spoke cavities and operate at 4.5 K?**

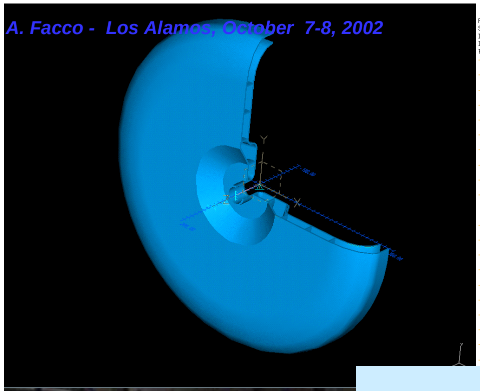
Discussion on "Consideration of 2K Operation" by Tsuyoshi Tajima

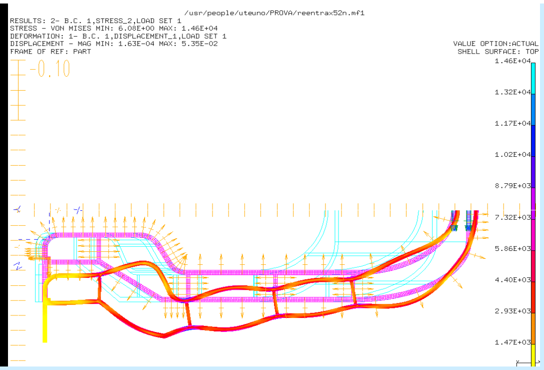
A comparison for 2K and 4K operation has been done for two cases: 10 nΩ and 1 nΩ residual resistance. Delayen pointed out that the 1 nΩ case corresponds to only 2 mG external magnetic field, which is achievable in a vertical test, but is difficult to achieve in a real accelerator tunnel.
The frequency dependency of losses favors spokes at 500 or 600 MHz. This is however not an option for AAA, as the frequency combination 350/700 MHz is set by the RFQ.
Pagani summarized that the achieved residual resistance, the static losses and microphonics issues are the real drivers of a 2K/4K decision. Kelley had shown, that important components (e.g. cryostat) are not affected a lot, the cost between the two options seems to be comparable. 2K is paying more for the cryoplant, 4K pays more in losses. Delayen added that the microphonics issue is mostly dominated by the beamloading for an operation scenario.

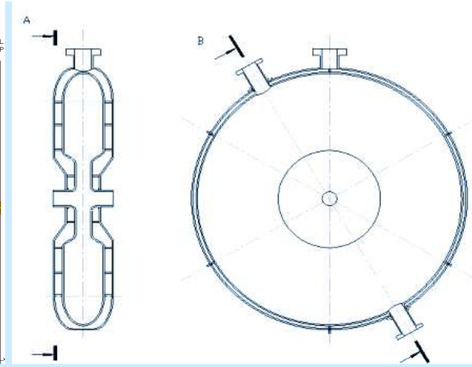
Development of a 352 MHz, low-β superconducting reentrant cavity at LNL

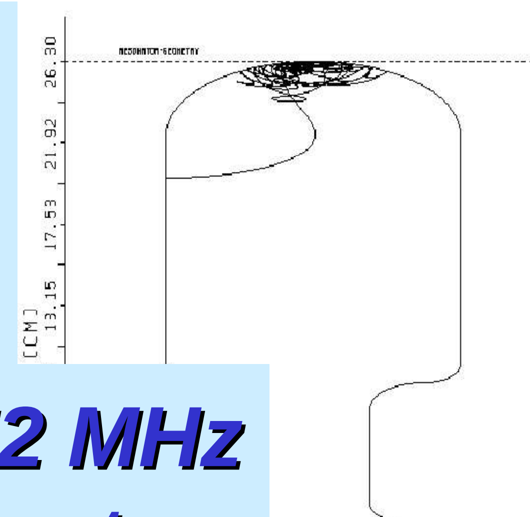
A. Facco, V. Zviagintsev, M. Pasini, F. Scarpa, D. Berkovits, Zhou Lipeng, INFN-LNL; E. Chiaveri, R. Losito, CERN

A superconducting reentrant cavity for low beta beams has been designed, built and tested at LNL after chemical polishing at CERN. This single gap resonator is a prototype for the low beta section of the TRASCO 30 mA proton linac, designed aiming at full beam transmission even in case of failure of one resonator. This 352 MHz single-gap cavity can be used at low energy down to β=0.1. An important feature of the mechanical design is the double-wall structure, allowing light weight and stability against helium pressure in spite of the large flat shape. The resonator internal profile was designed to prevent multipacting. The cavity was tested at 4.2 K, showing high gradient (7.5 MV/m at the nominal 7 W power) and no dangerous multipacting. For their compact size, field symmetry, wide velocity acceptance and low peak fields, reentrant cavities can play an important role in special applications of low-β linacs.

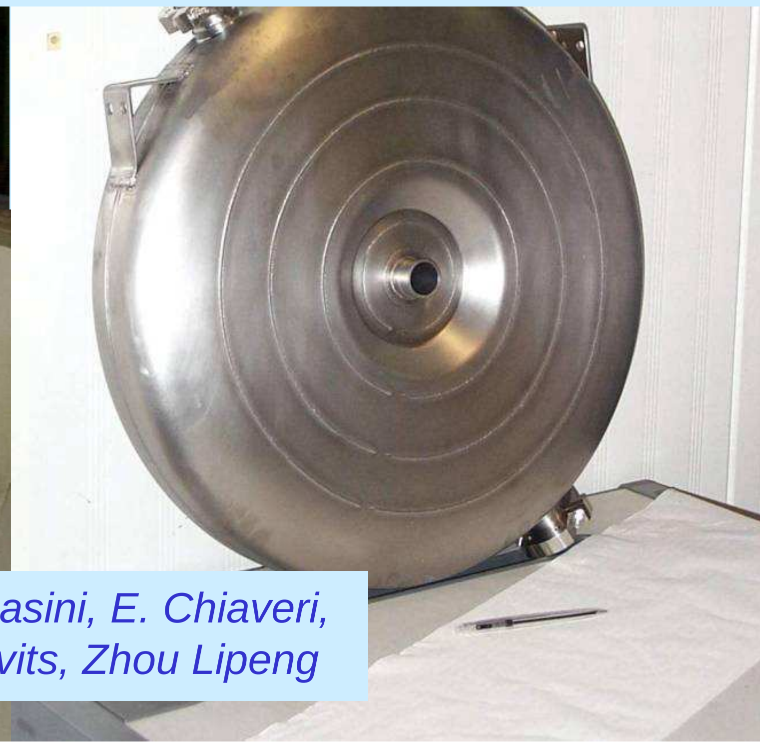








Development of a low-β , 352 MHz Superconducting Reentrant Cavity at LNL



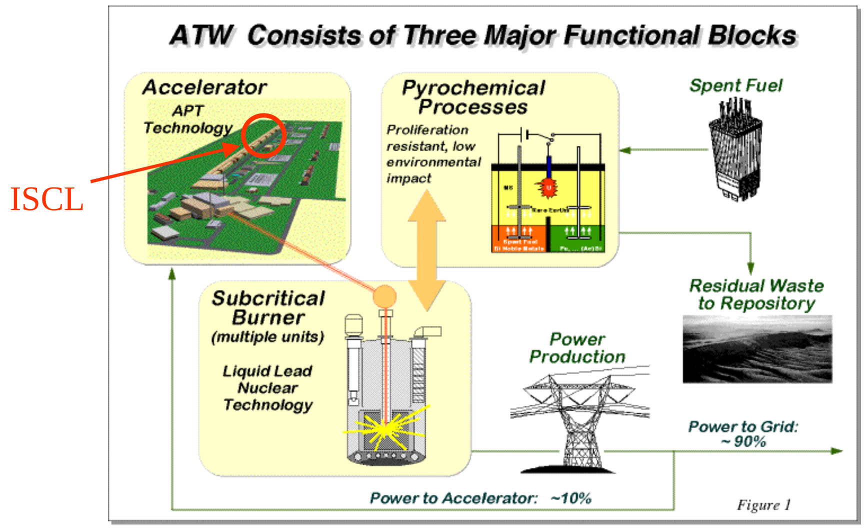
A. Facco, V. Zviagintsev, M. Pasini, E. Chiaveri,
R.Losito, F. Scarpa, D. Berkovits, Zhou Lipeng

Introduction

- We are developing low-β superconducting cavities for ADS applications (TRASCO)
- The TRASCO accelerator is a 1 GeV, 30 mA proton linac
- The intermediate energy part, 5-100 MeV, works at 352 MHz

- <u>Important constraint</u>: ADS systems with sub-critical reactors do not tolerate beam interruptions longer than ~1 s

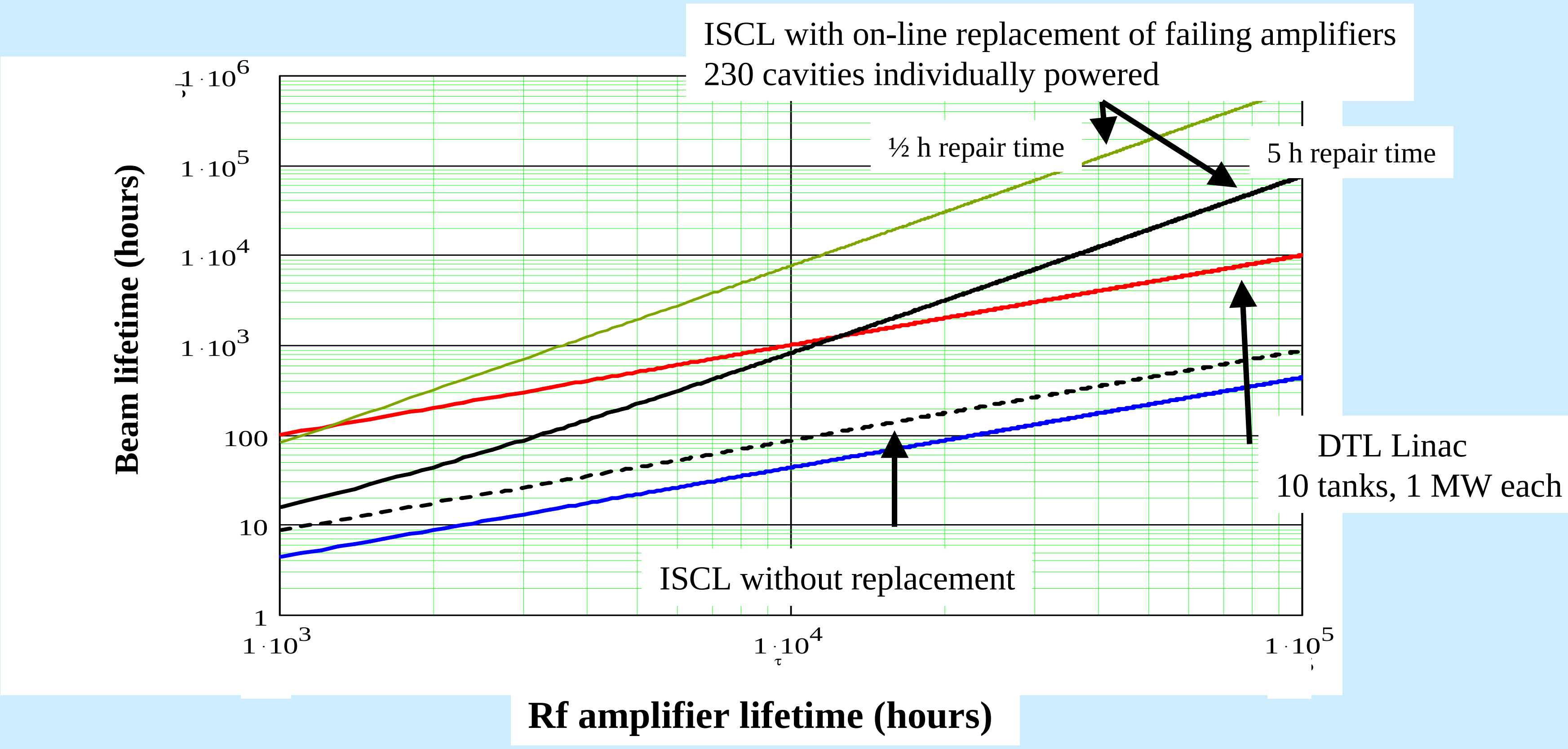
Accelerator Transmutation of Waste



Aim: Energy production and waste transmutation by means of an accelerator driven sub -critical reactor

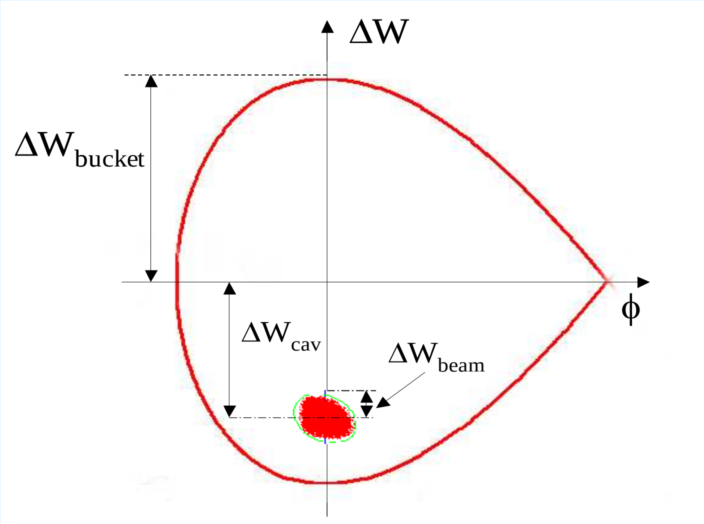
Beam lifetime in a repairable linac

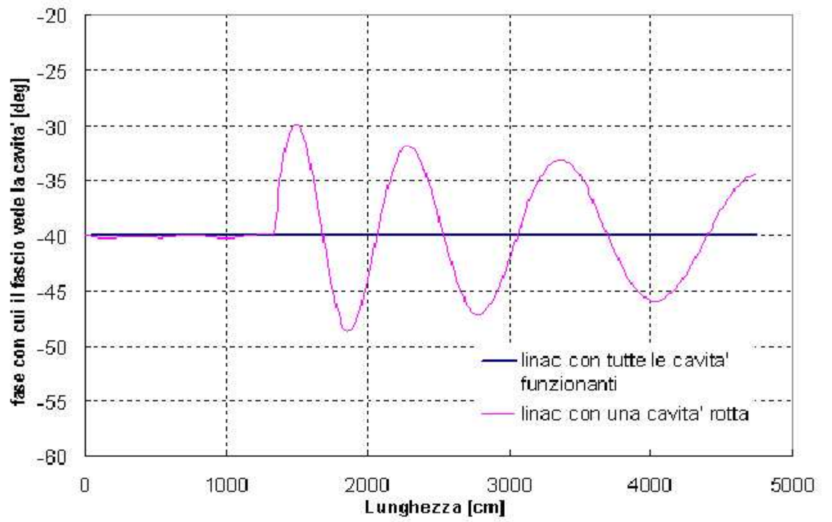
- Most beam interruptions come from failure of rf systems
- Beam lifetime can be improved significantly if the accelerator can tolerate the failure of one cavity and if this can be fixed on-line, e.g. replacing the power amplifier



Cavity constraints

- The linac can tolerate one cavity failure if the maximum energy gain per cavity is limited: $DW_{cavity} < DW_{bucket} - DW_{beam}$



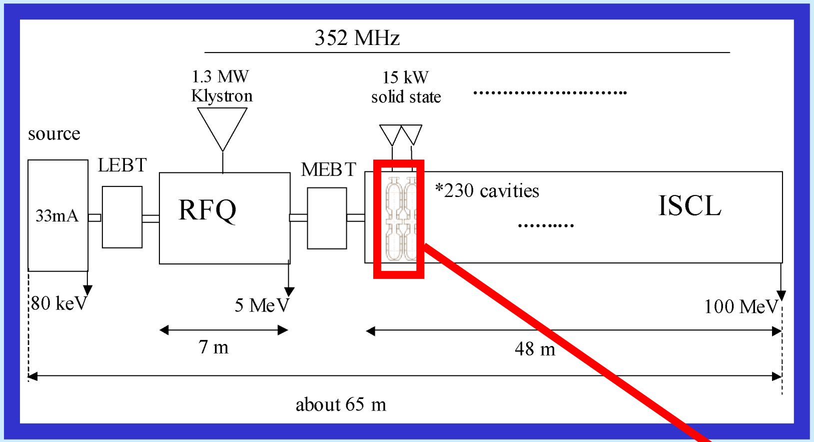


•Switching off one more cavity in the proper place allows to put back the beam in the center of the bucket

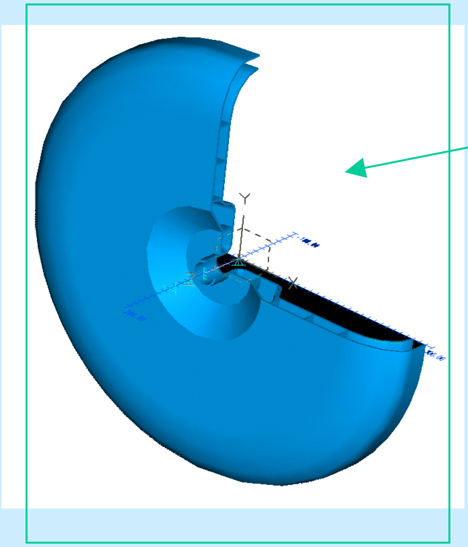
•Splitting the acceleration in many independent units, however, is not efficient in terms of R_{sh}: the superconducting solution is mandatory

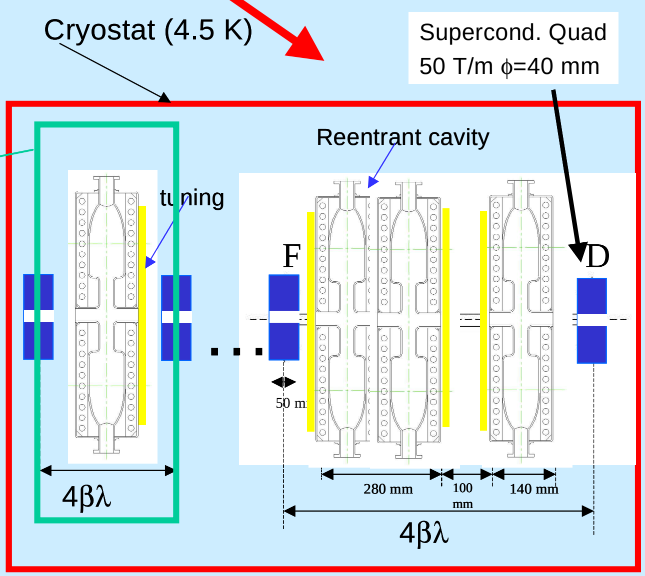
100 MeV TRASCO linac

tolerant of cavity failures



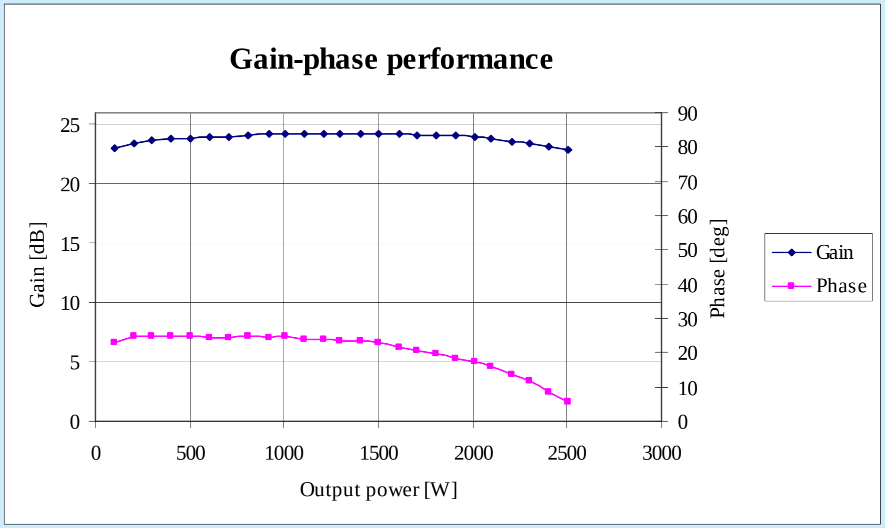
- 352 MHz, 30 mA proton RFQ
- 5-100 MeV ISCL
- FODO lattice
- wide-β SC cavities
- $\Delta W \leq$ 0.5 MeV/cavity (up to at least ~20 MeV)

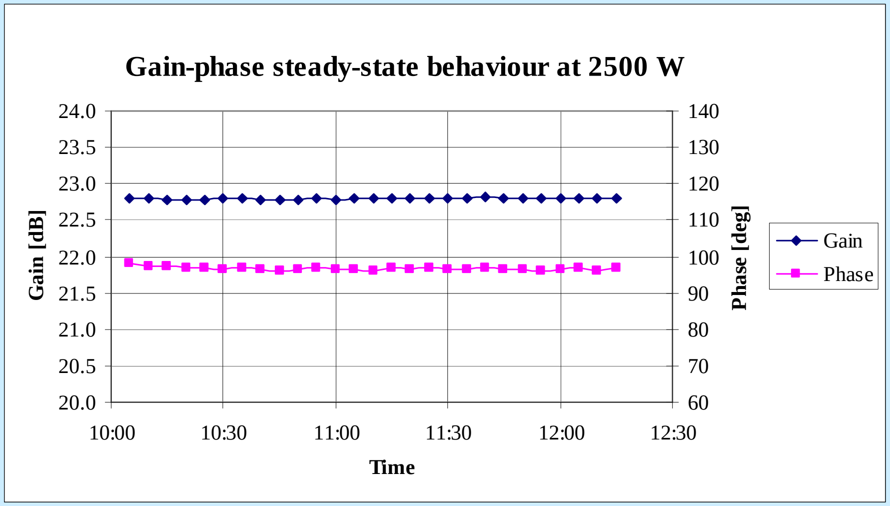


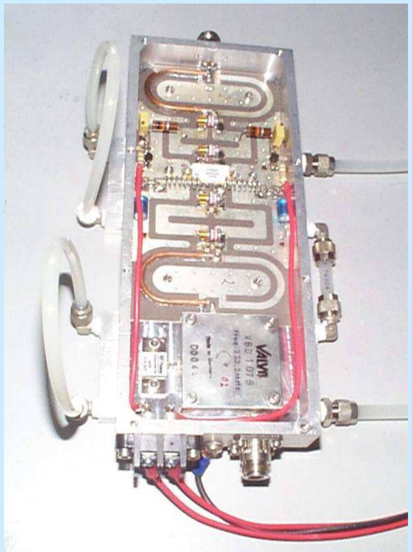


Required R&D:
- low cost - high reliability solid state amplifiers
- superferric quads
- <u>cavities</u>

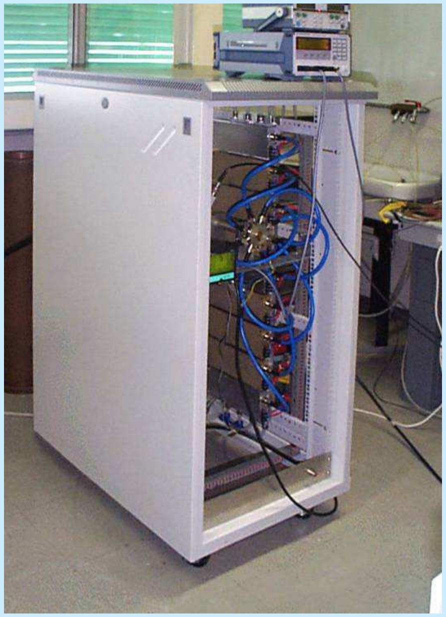
Low cost - high reliability solid state amplifiers







- **Modular construction**
- **MOSFET technology**
- **Circulators included**
- **Unconditionally stable**
- **Performance**
- **Reliability**



- **1st 2500 W amplifier constructed and successfully tested**

going on:

- Testing in severe conditions
- Engineering for production
- Design of 5-20 kW units

Superferric quadrupole magnet

• **Developed at MSU-NSCL in collaboration with INFN-LNL for superconducting linacs**

• **Very compact, to be used inside cryostats-magnetic shielding required**

• **tested at 300K; test at 4.2 K to be done**

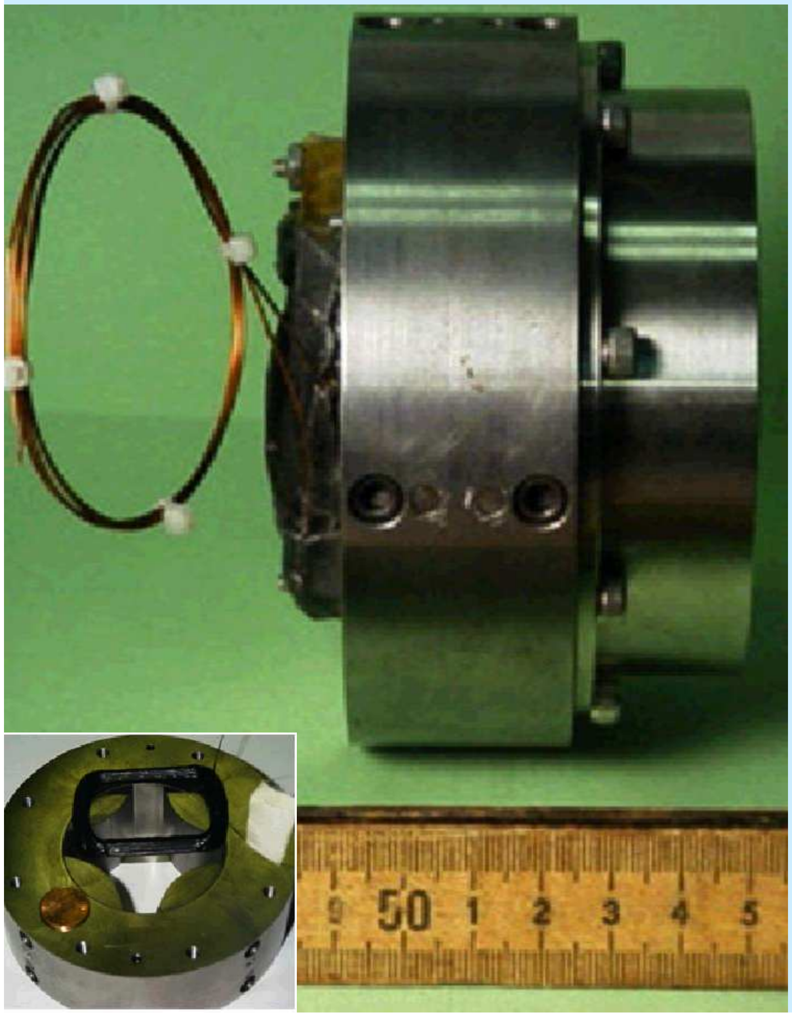
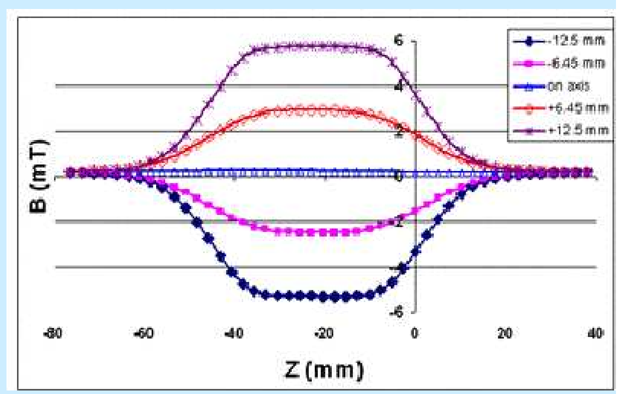
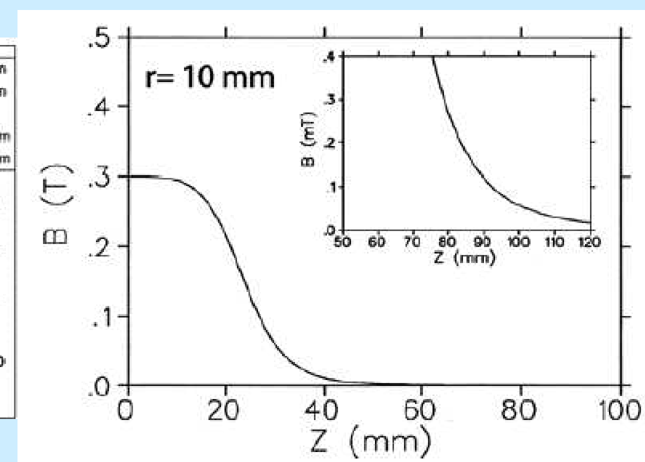


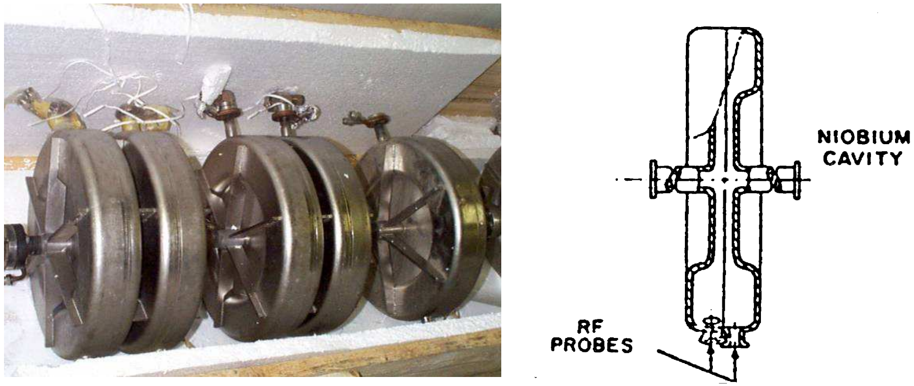
TABLE I
PHYSICAL PARAMETERS

Property	Specification
Effective length	50 mm
Radius	20 mm
Gradient	31 T/m
Turns of 0.431 mm wire	78
Current (2-D calculation)	63 A

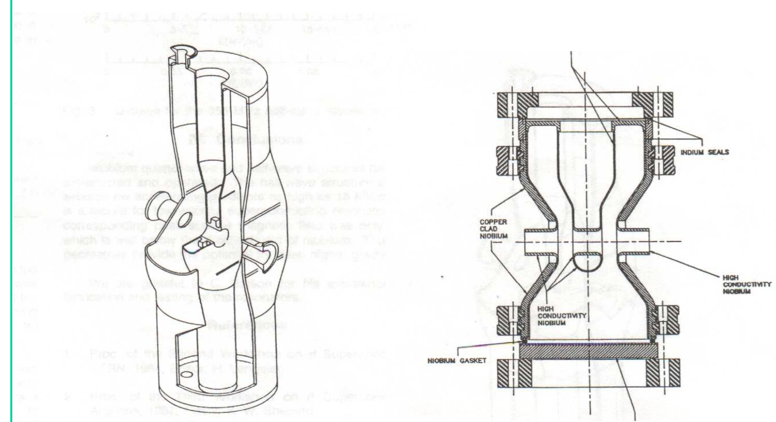




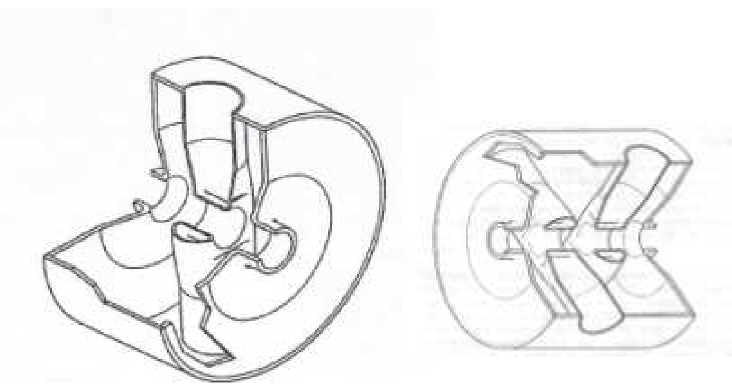
Examples of low-β cavities for proton beams



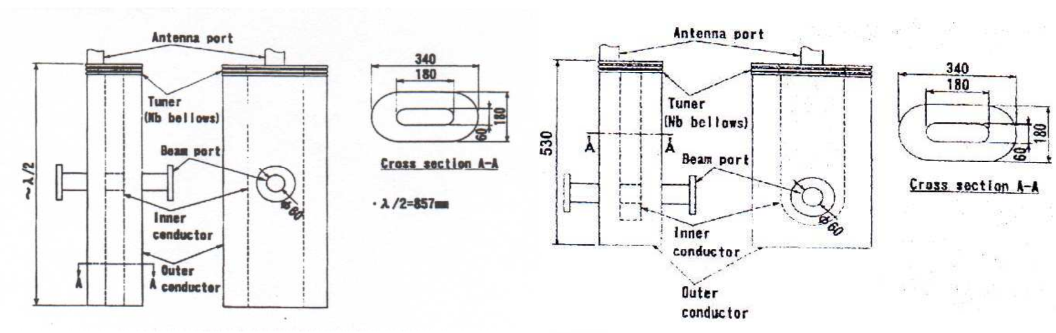
Stanford reentrant cavities (430 MHz)) -built and tested



ANL λ/2 (355 MHz) and λ/4 (400 MHz)-built and tested

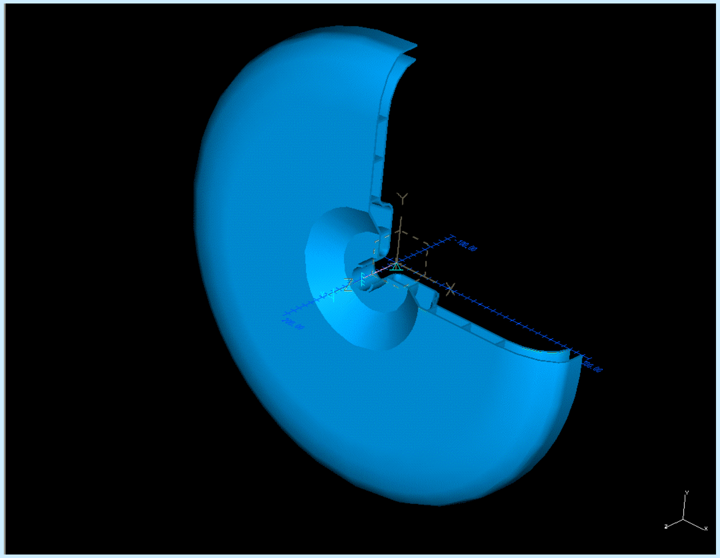


ANL 2-gap spoke (350 MHz) – built and tested
and 3 gap (850 MHz) spoke - proposed

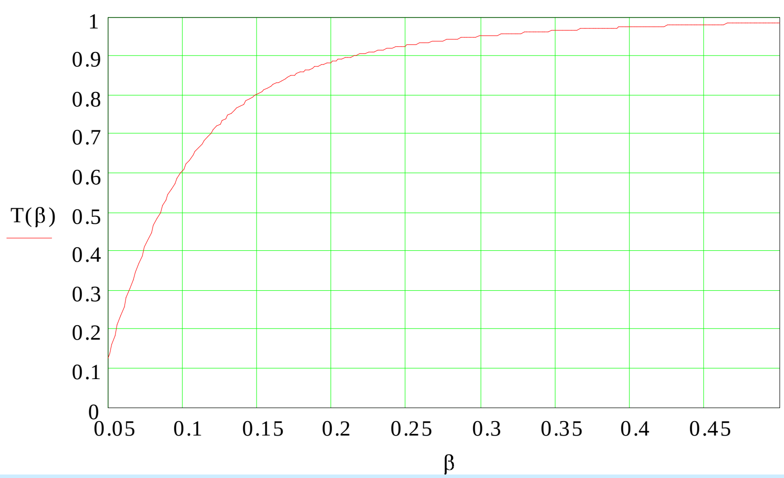


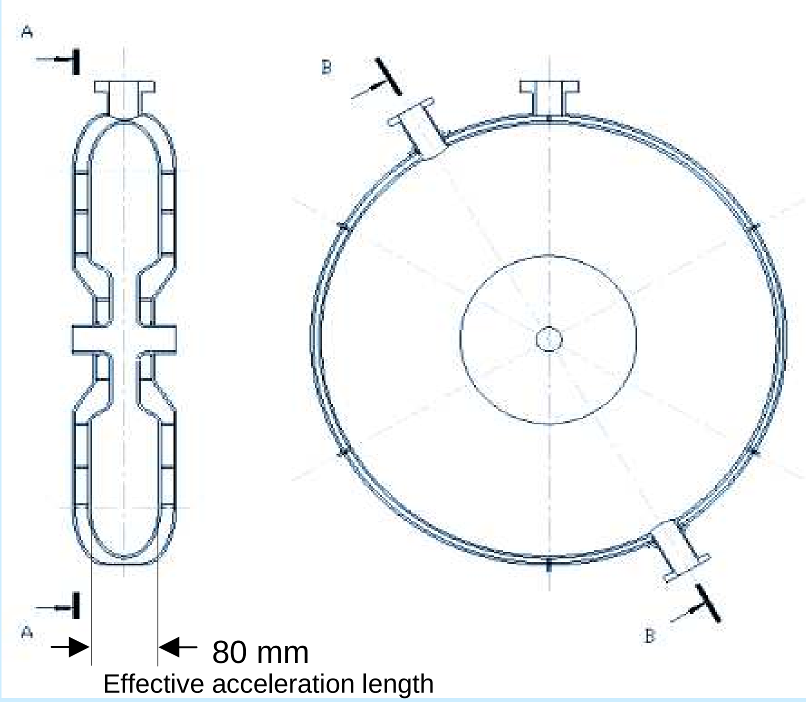
Toshiba λ/2 and λ/4 (175 MHz) - proposed

The TRASCO reentrant cavity

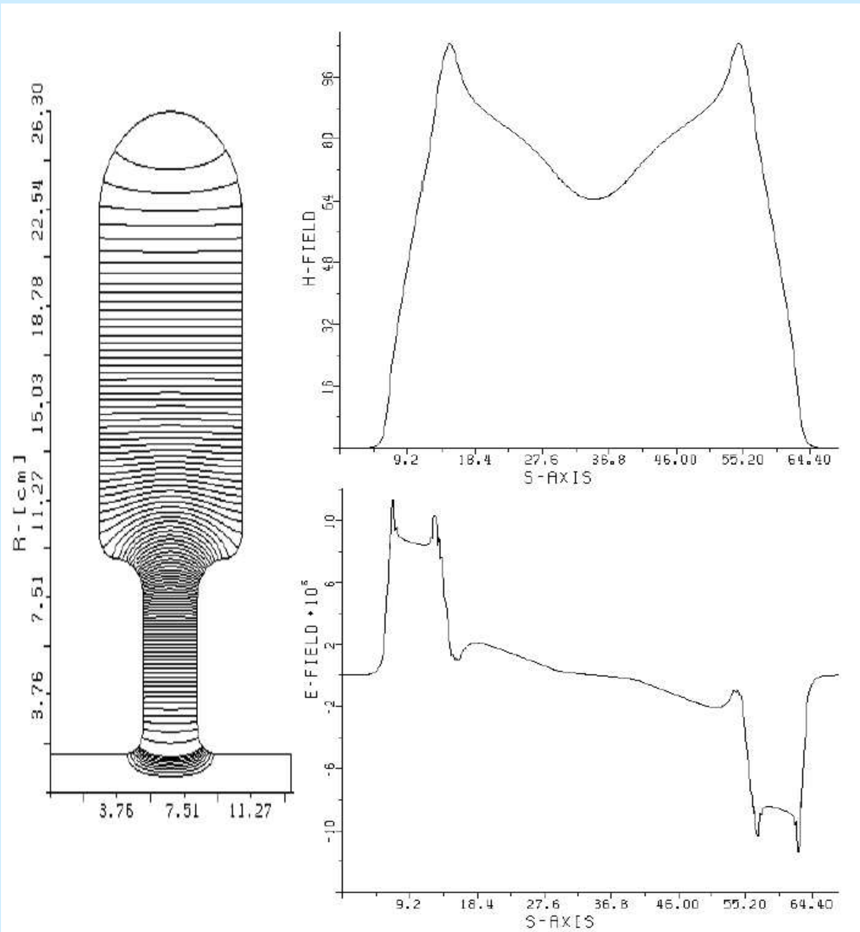


- 352 MHz cw
- single gap
- same cavity from 5 to 100 MeV
- Bore diameter 30 mm
- Field Axial symmetry





Rf design



In the final shape the intermediate step was smoothed to 60 deg

Main specifications:

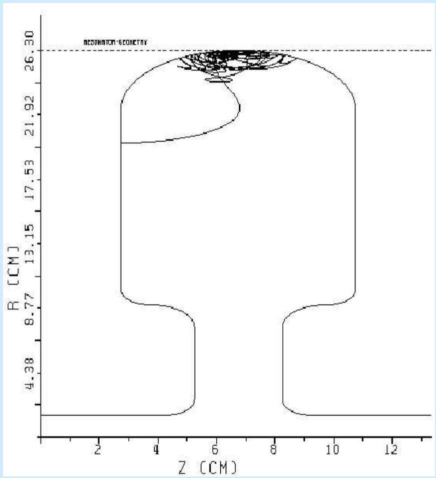
- 352 MHz, $\beta \geq 0.1$
- 30 mm bore diameter
- Inner length $\leq$ 80 mm
- $\Delta W \approx 0.5$ MV at 7W

Rf codes used:

- Superfish, HFFS

Cavity inner diameter	536	mm
Gap length	30	mm
Effective gap length	53	mm
Bore diameter	30	mm
Eff. acceleration length	80	mm
U/ E_a^2	0.034	J/(MV/m)
E_p/ E_a	3.0	
H_p/ E_a	3.1	mT/(MV/m)
$\Gamma = R_s \times Q$	83	Ω
R_{sh}/Q	84	Ω

Multipacting simulations

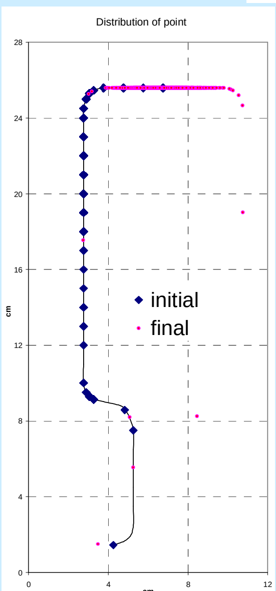


Simulation:

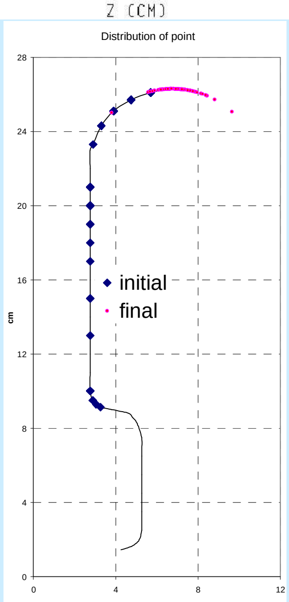
- code TWTRAJ (courtesy of R.Parodi, INFN Genova)
- ~60000 Runs
- 0.005 MV/m steps in E_a
- 5 mm steps in e^- starting position

Results:

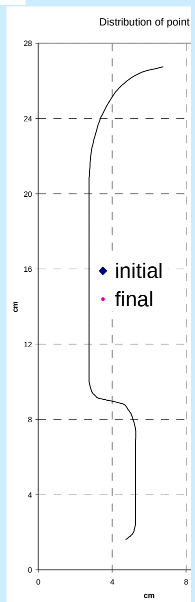
- MP negligible near the gap
- All levels at the equator: the equator profile is critical
- Ellipsoidal shape 1.5:1 free of MP



n. initial file 24020
n. selected file 1578
ratio 6.60%
range 0-25 MV/m



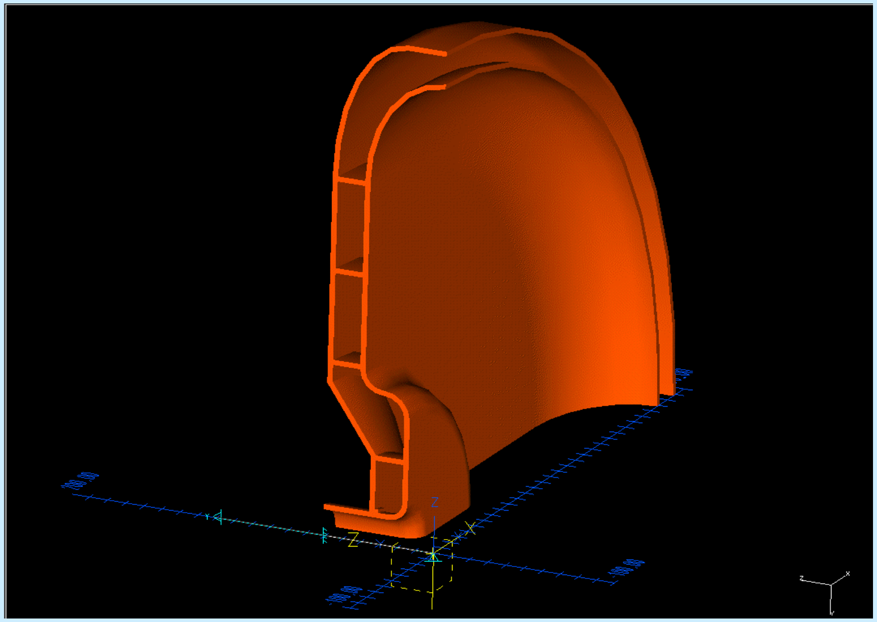
n. initial file 4840
n. selected file 95
ratio 2%
range 0-25 MV/m



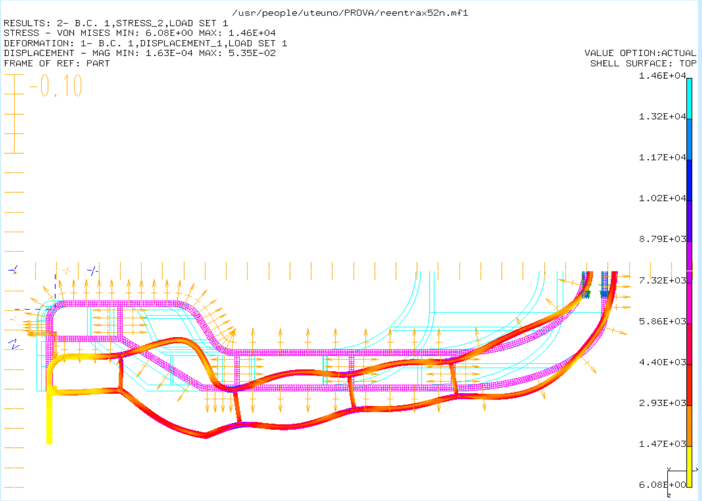
n. initial file 16516
n. selected file 0
ratio 0%
range 0-25 MV/m

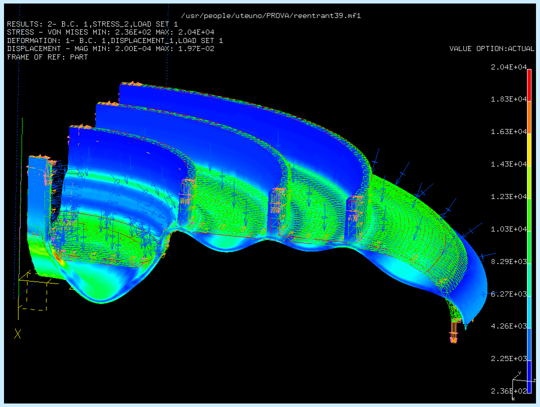
Total Number of runs with TVTRAG 45376

Mechanical design



- Main constraints:
  - -4 bar max pressure
  - -Physical length without tuner <130 mm
  - -Stability against He pressure fluctuations
  - -tunability
- Double wall structure with interconnecting rings
- 3 mm thick niobium sheet
  - -Inner shell: RRR>150 Nb
  - -Outer shell: normal grade Nb





- codes used:
  - Autocad (preliminary)
  - I-DEAS (main)

Mechanical construction

- Designed at LNL
- Built at Zanon, Schio (Vicenza) Italy
- CP treated at CERN
- Tested at LNL

Inner shell

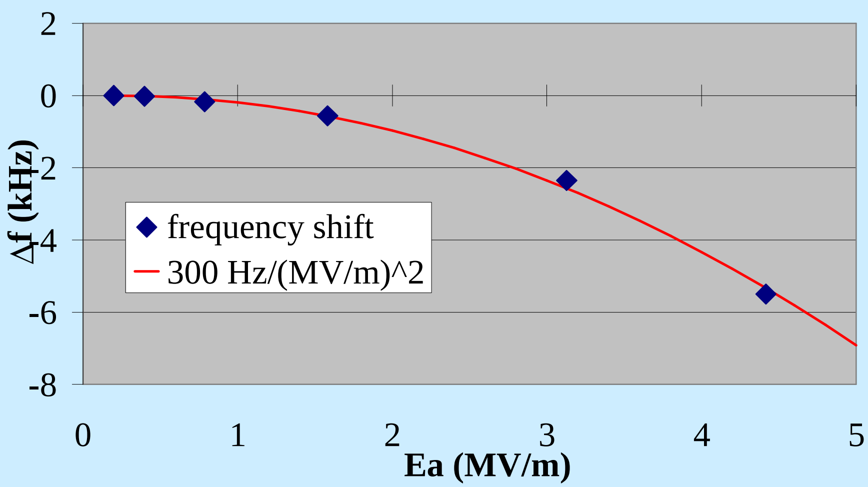
Detail of the interconnecting rings

Side view with rf ports

Final cavity after welding of the outer shell

Mechanical test results

(naked resonator - no tuner nor reinforcement)

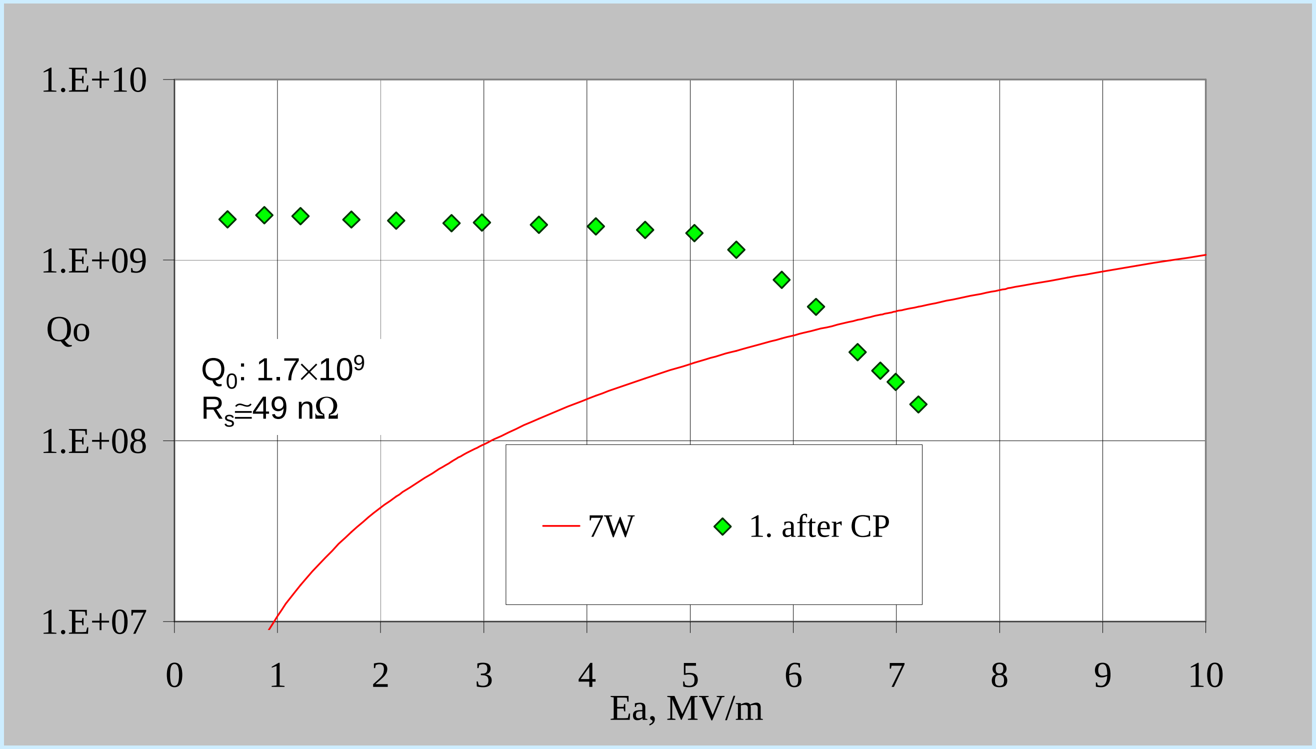


Lorenz force detuning test

parameter	measured	calculated	units
Rf frequency f final adjustment by plastic deformation foreseen	348.673	352	MHz
Frequency response to pressure df/dP from 0 to 1 bar in the helium vessel	~ -258	~ -140	Hz/mbar
Lorenz force detuning df/dE$_a$ measured from 0.2 to 4.4 MV/m	~ -300	~ -170	Hz/(MV/m)^2
Lower mechanical mode frequency f$_{mech}$	~ 195	~ 200	Hz

Superconducting Reentrant Cavity
1st Rf test at 4.2K

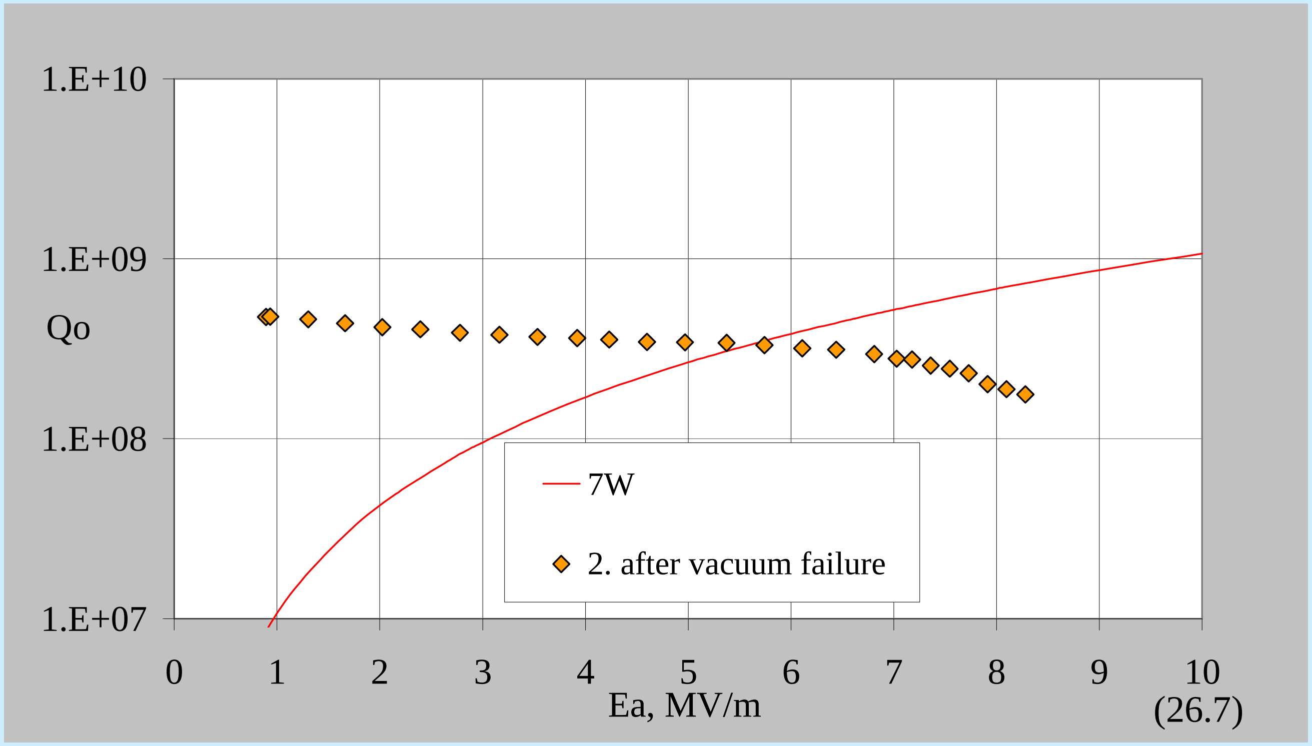
1st test (after CP): capacitive coupler at the beam port
insufficient coupling: MP and Rf conditioning impossible



- Low field MP disturbing the test
- **High Q_0: 1.7×10^9 Low field R_s≅49 nΩ (R_{res} ≅ 10 nΩ)**
- Strong field emission above 5 MV/m

Superconducting Reentrant Cavity
2nd Rf test at 4.2K

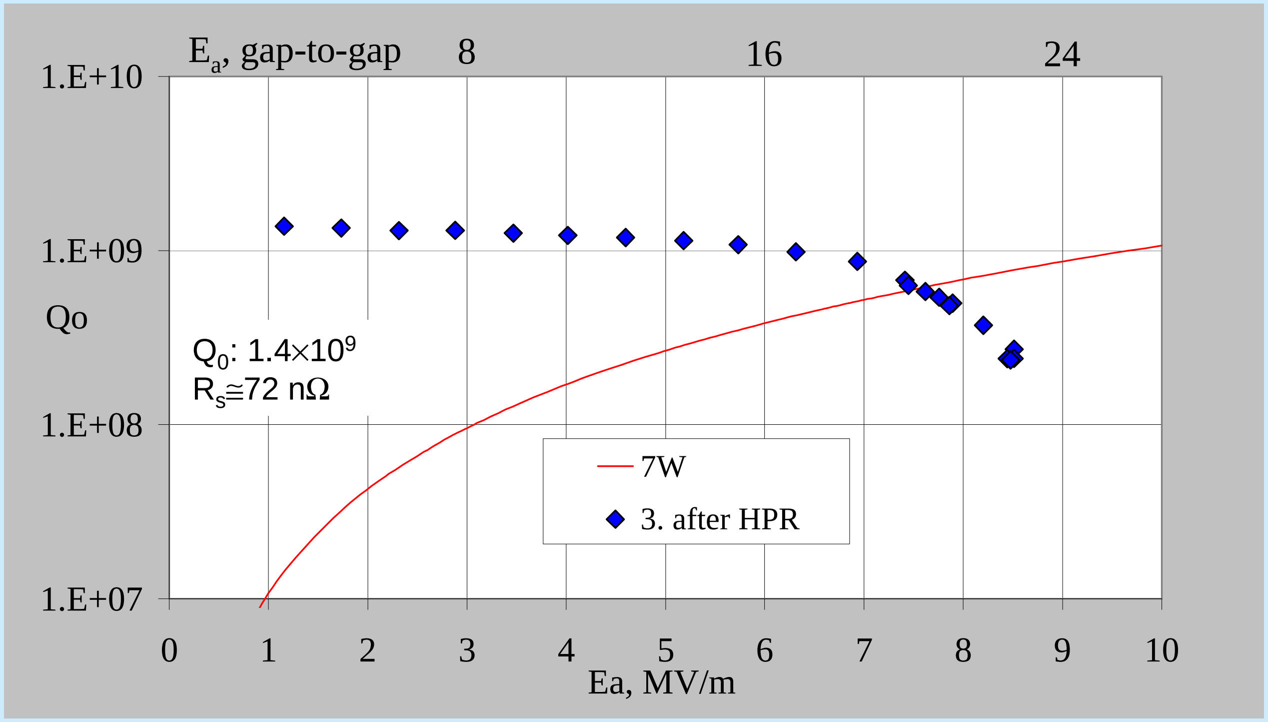
2nd test (after severe vacuum failure due to rf feedthrough burning; cavity exposed to dusty air during repair). Coupler problems fixed; MP and rf conditioning possible



- low field MP easily conditioned
- contamination with dust and burning residues: Q degradation
- Increased E_a, FE conditioned

Superconducting Reentrant Cavity
3rd Rf test at 4.2K

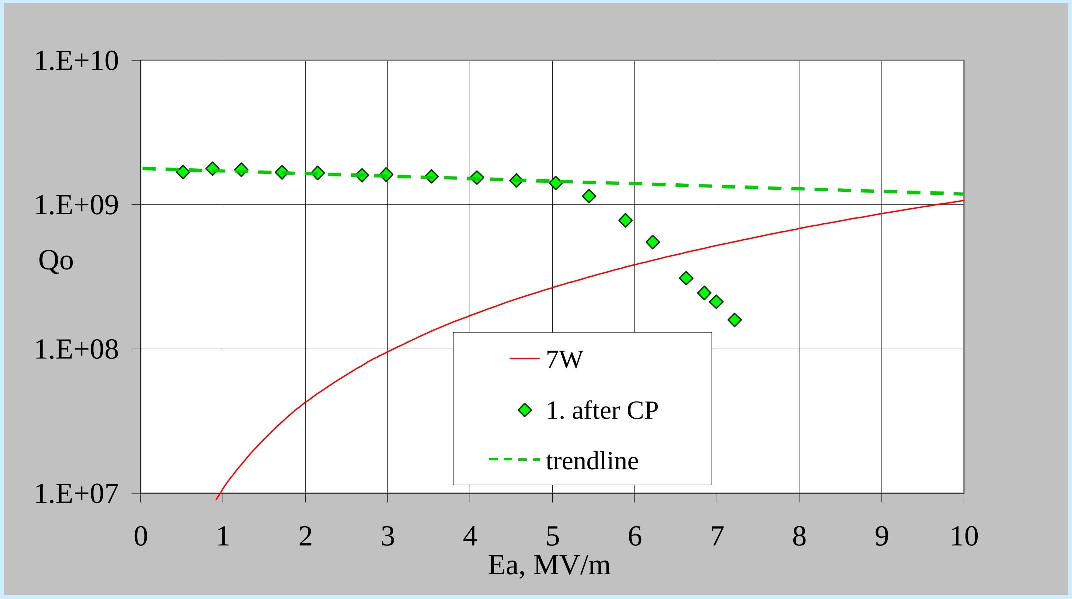
3rd test after HPR of the cavity from outside through rf- and beam- ports.



- no MP level above 0.03 MV/m; low field levels easily conditioned
- Q_0 partially recovered: $R_s \cong 72$ nΩ ($R_{res} \cong 33$ nΩ)
- E_a=7.5 MV/m @ 7W (0.6 MV)

Next steps

- HPR from inside and test again
- Build and test the tuner
- Build a 5 kW rf coupler for the SPES project



Considering the surface resistance measured in the first test, and the relatively low peak fields reached, we can expect further improvement of the 7 W gradient

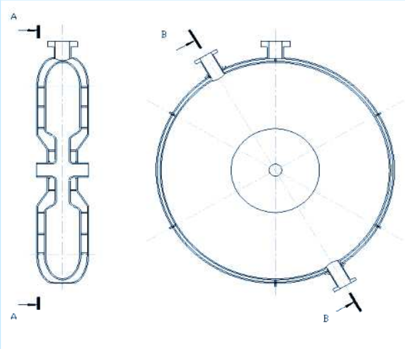
TRASCO Reentrant Cavity: advantages and drawbacks

Advantages:

- Short, compact and light, the He tank is part of the structure
- Relatively simple construction
- EM field perfectly symmetric
- very wide β acceptance
- Usable from very low energy (~5 MeV protons, $\beta \sim 0.1$)
- Low peak fields: possibility of high gradient

Drawbacks:

- not recommended for pulsed operation (Lorenz force detuning)
- relatively low energy gain/cavity
- Only inductive couplers to preserve compactness



Conclusions

•We have studied a high reliability design for the 30 mA, 5-100 MeV proton linac of TRASCO, based on reentrant cavities

- We have designed, built and tested a 352 MHz superconducting reentrant cavity
  - Short (13 cm without tuner) and very low β
  - free of dangerous multipacting
  - high gradient: 7.5 MV/m measured at the nominal power of 7 W
  - low peak fields: space for significant improvements

• Reentrant cavities possess some unique features that can be profitably used in low-β linacs, especially in the range $0.1 \leq \beta \leq 0.2$

Discussion on "Development of a 352 MHz, low-β Superconducting Re-entrant Cavity at LNL" by Alberto Facco

Some results were clarified during the discussion. The tuning sensitivity is about 0.5 MHz/mm, which agrees with the simulations. The Lorentz Force Coefficient has been calculated for the unconstrained case and will be smaller in a real environment. The tuning force is about 1000 N.

Rusnak pointed out that the maximum voltage obtained for this cavity so far is below the voltage, where the Hatch diagram predicts the onset of 2-point multipacting. For a 30 mm gap at the iris 2-point multipacting would start around 800 kV. Thus the cavity might be limited to the gradients obtained so far (that correspond to approximately 700 kV). Facco answered that also for other reasons the achievable gradient for this structure is limited to 800 - 1000 kV.

The compact structure lends itself to strong focusing lattices. This allows small apertures. Facco has not investigated the lower limit in β, where such a cavity could be used. Their study was in the framework of a 5 MeV RFQ.

Shepard suggested to present the results of this "multipacting free" resonator to the Stanford group, whose HEPL cavity in the 1970s was the first re-entrant superconducting design.

Delayen expects HOM problems in this structure for beam currents above 30 mA. Facco answered that for the planned cw-operation simulations have been done and problems are not expected.

The final discussion focused on the real estate gradient that can be achieved (in the TRASCO design). The TRASCO design accumulates 100 MV over a length of 50 m with this structure, which corresponds to 2 MV/m at peak fields less or equal about 24 MV/m and 40 G. There might be a modification of this number, as the design has not advanced to the point, where the cavity spacing including cryomodule, warm-to-cold transitions etc has been established.

The Multi-Cell SC CH-Cavity

A. Sauer, University of Frankfurt

The CH cavity is a multi-gap drift tube structure operated in H210 mode currently under development in a collaboration between IAP Frankfurt and GSI. Like the IH cavity (H110 mode) used at different places now for the acceleration of ions, this structure provides a high shunt impedance and allows the acceleration of intense beams at high accelerating gradients.

The dedicated KONUS beam dynamics used for H-mode cavities results in long lens free sections (like the High Current Injector at GSI), making the design of a superconducting CH resonator possible. An other aspect of the investigations started at GSI and IAP Frankfurt is to extend the attractive velocity range of H-mode cavities up to beta=0.5 by these actual devel-opments.

Many future projects (the Accelerator Driven System ADS, International Fusion Material Irradiation Facility IFMIF, European Spallation Source ESS and Spallation Neutron Source SNS) are based on the availability of efficient accelerating cavities with properties like mentioned above. Other applications as envisaged within future projects are cw operation of pro-ton or ion accelerators. It is commonly accepted that above an energy of 200 MeV/u superconducting cavities are superior to room temperature structures at duty cycles above a few percent. By combining the advantages of CH-mode cavities with the benefits of superconductivity, effective ion acceleration at high duty cycle and at low injection energies will become possible. For high current proton beams the injection energy will be around 10 MeV, while for heavy ions the injection energy may become as low as 1 MeV/u.

Our investigations indicate that CH-mode cavities are well suited to design superconductiong resonators. The results of the numerical simulation and the first measurements of a room tem-perature model cavity are very promising. Using state of the art technology the fabrication of a s.c. CH-mode cavity will be possible. A design study in close cooperation with industry will be available in one year. The cryostat, the laminar flow box and the fluid He dewars with the recovery system is already available.

The Multi-Cell SC CH-Cavity

A.Sauer, H.Podlech, H. Liebermann, U.Ratzinger

Workshop on the Advanced Design of Spoke Resonators

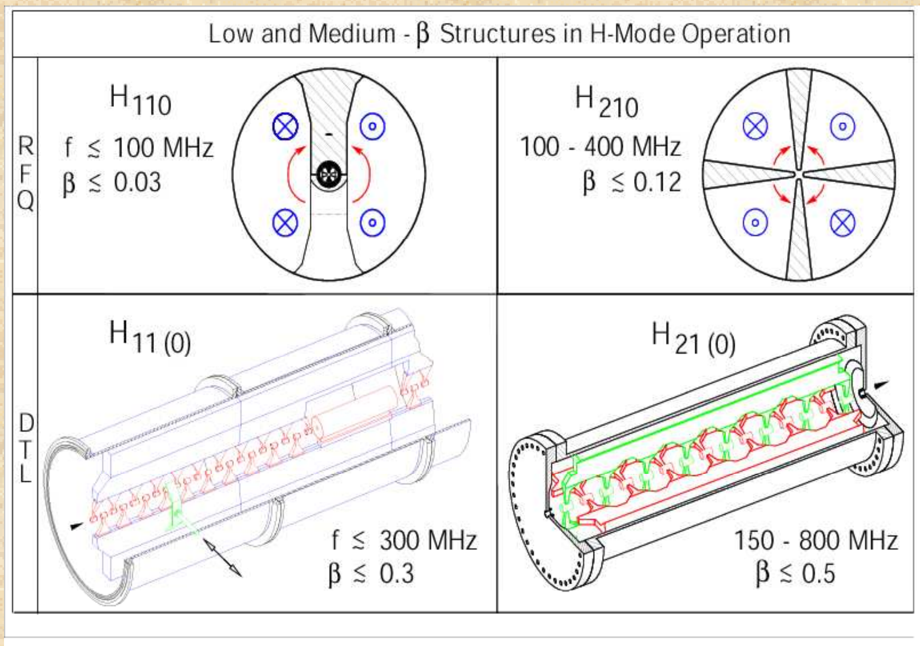
October 7 and 8, 2002
Los Alamos, NM, USA

Content

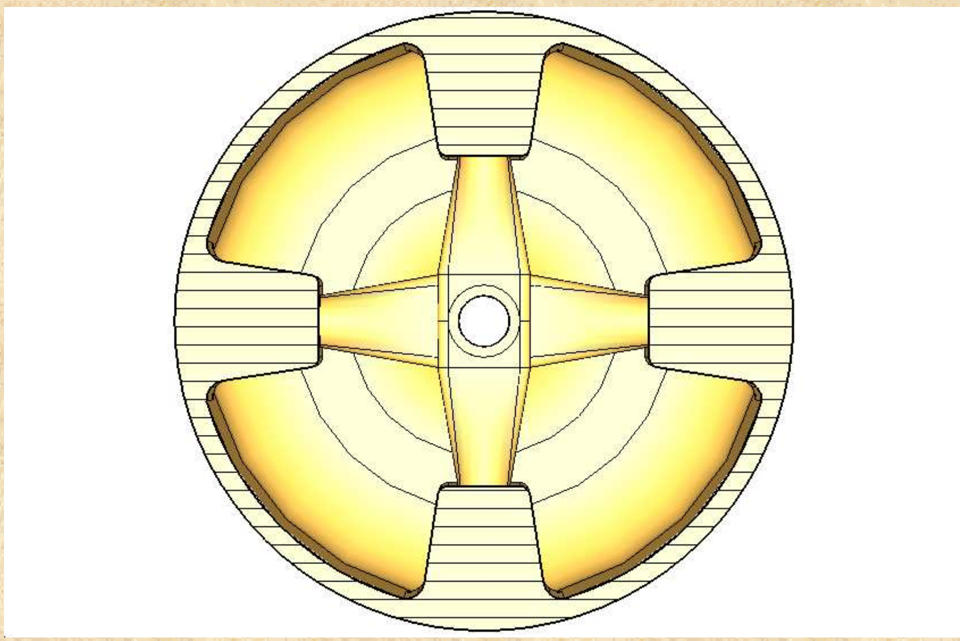
- The H_{210}-mode
- Prototype development
- Possible applications
- Conclusions

The H_{210}-mode

➔ 4-Vane-RFQ with short circuited dipole modes:



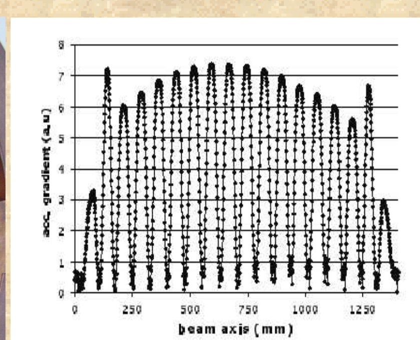
➔ Cross-Bar-Array:



Prototype developments

➔ rt CH copper model: 1.) Analyzing higher order modes (near future) and field flatness, 2.) Optimization of end cell geometry

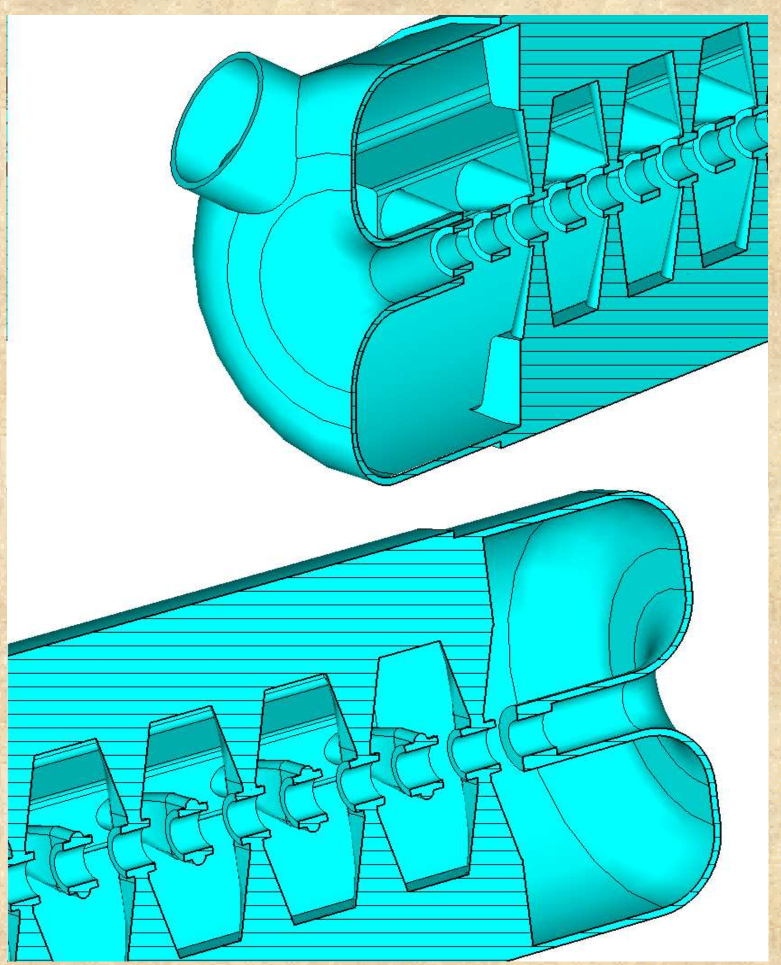
➔ sc prototype geometry based on Micro-wave Studio simulations (protons,I=200❍A)

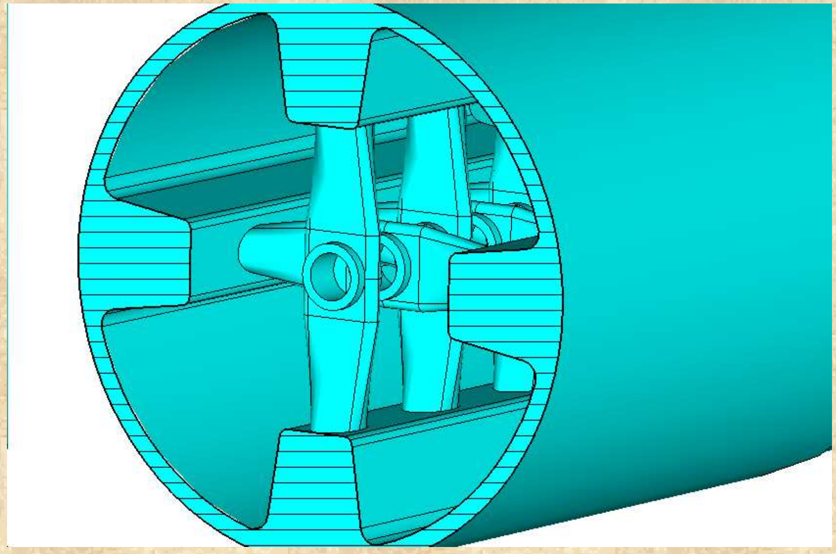


On axis field (bead pull setup)

Frequency:	**352 MHz**
Beta:	**0.1**
Tank length:	**1.06 m**
Number of gaps:	**19**
DT diameter	**2.5 cm**
E_{acc}	**5.0 MV/m**
B_{peak}	**36 mT**
E_{peak}	**25 MV/m**
Tank diameter	**29 cm**

➔ Detailed views of the prototype:





➔ Microphonics simulations studies underway with the program COSMOS

➔ Lorentz force detuning simulations up to now not planned (cw operation and low acceleration fields $E_{acc} \approx 5$ MV/m)

➔ Status of the cryogenic laboratory: Cryostat, magnetic shielding, laminar flow box class 100, fluid He from TU-Darmstadt in 250 l dewars, He recovery system

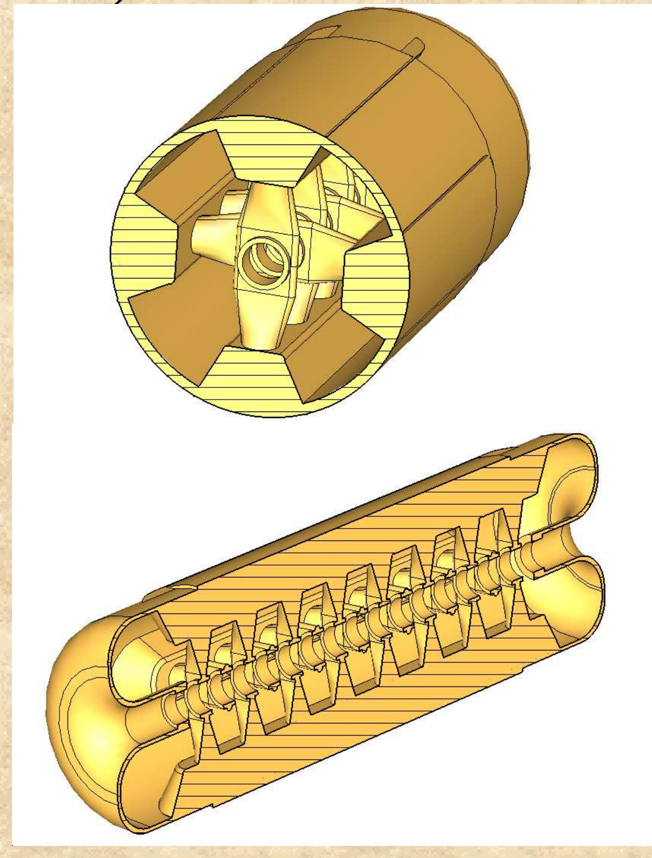
➔ Technical design in progress and in close cooperation with industry:

- bulk Niobium
- RRR-value: ≥ 250
- material costs: ≈ 100 k$
- thickness about 3 mm
- 4 K operation temperature (first step)
- 100 W Amplifier is foreseen (variable frequency 300 – 600 MHz)
- connection of the resonator components with electron beam welding
- magnetic coupling (first attempt) but with options for electric coupling

➔ at present call for tenders for prototype fabrication

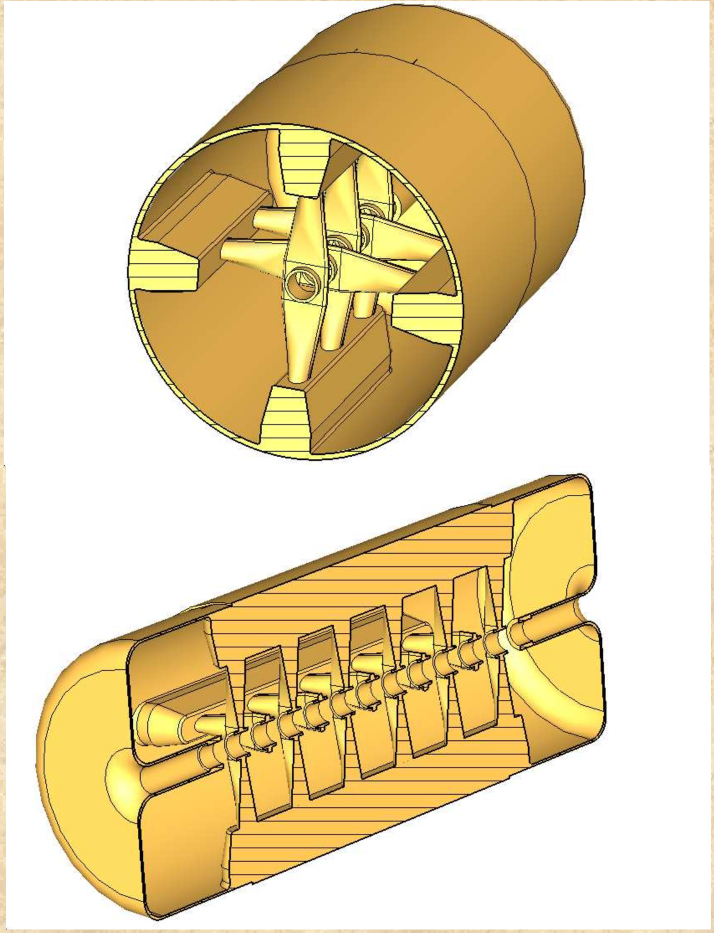
Possible applications:

➔ cw 350/700 MHz, < 40 mA, 100 MeV proton beams for ADS (Accelerator Driven System)



Beta:	**0.1**	**c**
Frequency:	**350.43**	**MHz**
E_{acc}:	**5.29**	**MV/m**
E_{peak}:	**25.1**	**MV/m**
B_{peak}:	**44.6**	**mT**
Tank length:	**0.936**	**m**
Drift tube diameter:	**4.0**	**cm**
Tank diameter:	**26.8**	**cm**
Number of gaps:	**16**	
E_{peak}/E_{acc}:	**4.75**	
B_{peak}/E_{acc}:	**8.43**	**mT/MV/m**

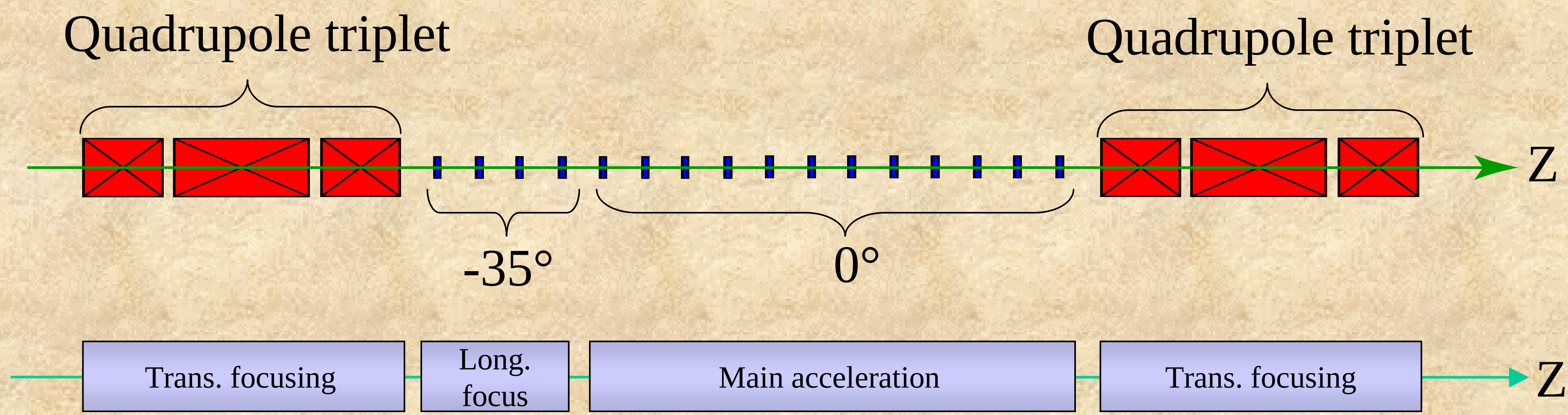
➔ cw 175 MHz, 125 mA, 40 MeV deuteron beams for IFMIF (International Fusion Material Irradiation Facility)



Preliminary (Optimization necessary)

Beta:	**0.1**	**c**
Frequency:	**174.86**	**MHz**
E_{acc}:	**5.35**	**MV/m**
E_{peak}:	**38.7 → < 30**	**MV/m**
B_{peak}:	**49.1**	**mT**
Tank length:	**1.52**	**m**
Drift tube diameter:	**5.0**	**cm**
Tank diameter:	**58.0**	**cm**
Number of gaps:	**12**	
E_{peak}/E_{acc}:	**7.23**	
B_{peak}/E_{acc}:	**9.17**	**mT/MV/m**

- Dedicated for the KONUS (Kombinierte Null Grad Struktur) concept
  → long lens-free sections



Conclusions

- The sc CH-capabilities are promising
- Multicell sc CH design is attractive for fixed velocity, high current linacs
- Prototype development is in progress
- The first sc CH prototype cavity is expected to be ready for testing at the end of 2003

For more informations: Internet: http://iap-ffm.de

Email: **h.podlech@iap.uni-frankfurt.de || a.sauer@iap.uni-frankfurt.de**

Discussion on "The Multi-Cell SC CH-Cavity" by Andreas Sauer

The application for this structure could be an ADS type machine (cw, up to 40 mA current, 350 or 700 MHz). The beam dynamics for such a long structure (16 gaps) is the KONUS dynamics. There are 2 quad triplets before and after the structure (first FDF then DFD) for transverse focusing. The longitudinal focusing is done in the first 1 to 4 gaps of the cavity, the rest of the gaps is for acceleration.
Sauer compared the CH structure with the better known room-temperature IH structure. The IH structure uses a H_{110} mode, CH uses H_{210}, as a result for the same frequency the IH structure is more compact. The interdigital loading makes the IH structure less stiff, the cross-bar loading of the CH structure makes it very stiff and well suited for SC application.
The Frankfurt/GSI interest in these structures is the high real estate gradient of these structures. At GSI a low-β IH structure has been operated at 10 MV/m. The proposed application is for a β=0.1 structure for an energy range of 5-8 MeV, this could be followed by a second CH-structure at β=0.2.

RF-Focused Spoke Resonator

A. Garnett, Los Alamos National Laboratory

We will discuss the feasibility of using finger-like structures added to a spoke resonator cavity to superimpose a modest amount of electric quadrupole focusing onto the high axial accelerating field. The motivation for this idea is to possibly eliminate the need for magnetic focusing elements such as solenoids between the spoke cavities in a cryomodule at very-low beam velocities. This greatly improves the real-estate accelerating gradient by increasing the longitudinal packing factor. So far, proposed linac designs using spoke resonators at low- have not been able to take full advantage of the high gradients available in these superconducting structures due to the high longitudinal phase advance per period resulting from long focusing periods caused by engineering constraints. The resulting reduction in drift distances between accelerating cavities reduces the longitudinal phase advance per period and allows the use of higher accelerating gradients. Preliminary results of cavity modeling and analytical calculations for the proposed structure will be discussed.

This work is supported by the U. S. Department of Energy Contract W-7405-ENG-36.

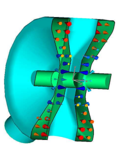
RF-FOCUSED SPOKE RESONATOR

R. W. Garnett, F. L. Krawczyk, R. L. Wood, and D. L. Schrage
Los Alamos National Laboratory

Workshop on the Advanced Design of Spoke Resonators

Los Alamos, NM, USA
October 7 and 8, 2002

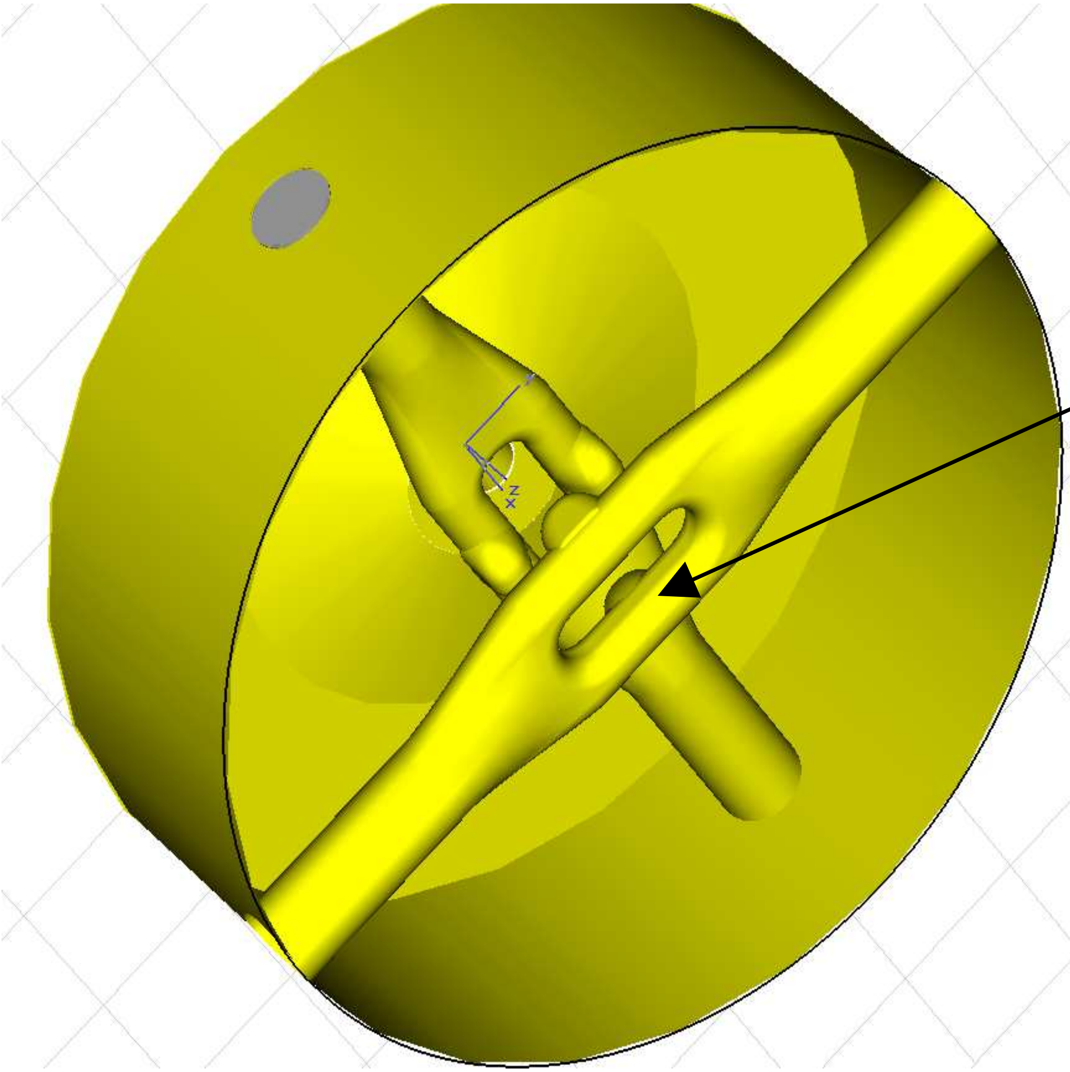
Work supported by the US Dept. of Energy



Abstract

In this paper we discuss the feasibility of using finger-like structures added to a superconducting spoke resonator cavity to superimpose a modest amount of electric quadrupole focusing onto the high axial accelerating field. The motivation for this idea is to eliminate the need for magnetic focusing elements such as solenoids between spoke cavities in a cryomodule at very low beam velocities and thereby improving the real-estate accelerating gradient by increasing the longitudinal packing factor. So far, proposed linac designs using spoke resonators at low-β have not been able to fully take advantage of the high gradients available due to the high longitudinal phase advance per period caused by engineering constraints. Preliminary results of cavity modeling and analytical calculations for the proposed structure are discussed.

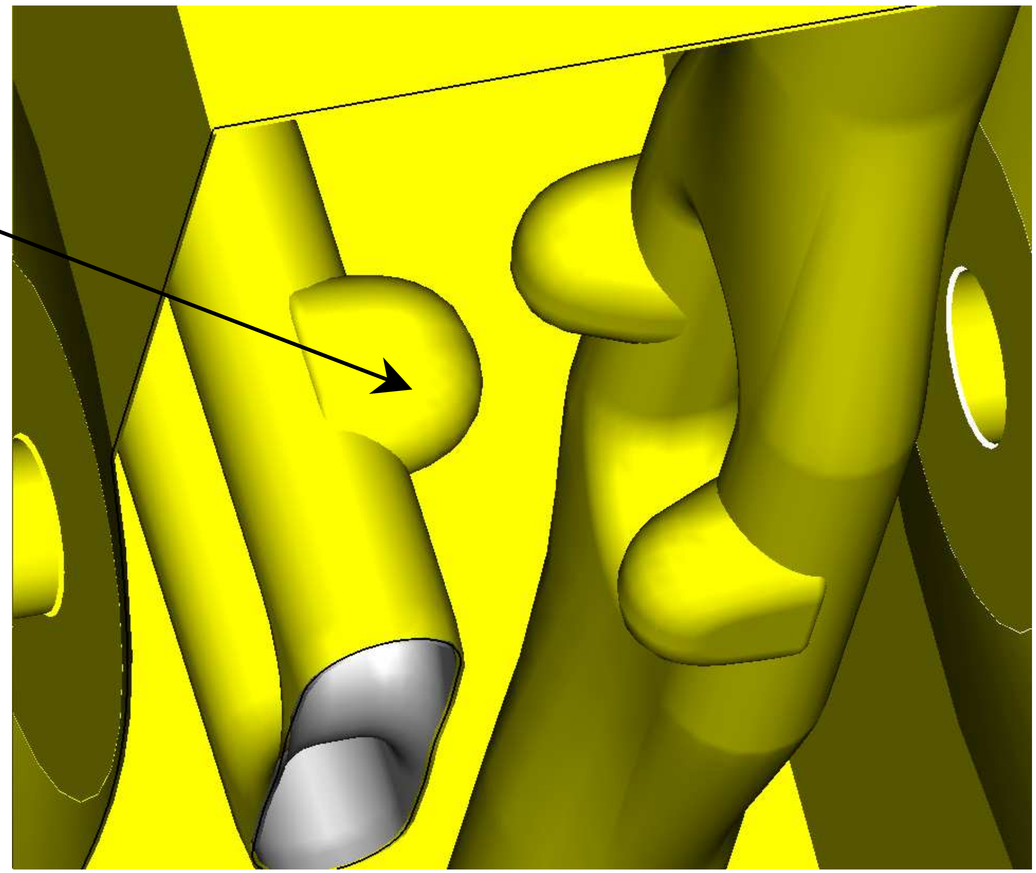
Spoke Cavity Cut-Away View



Elongated beam aperture reduces peak surface fields and cavity capacitance.

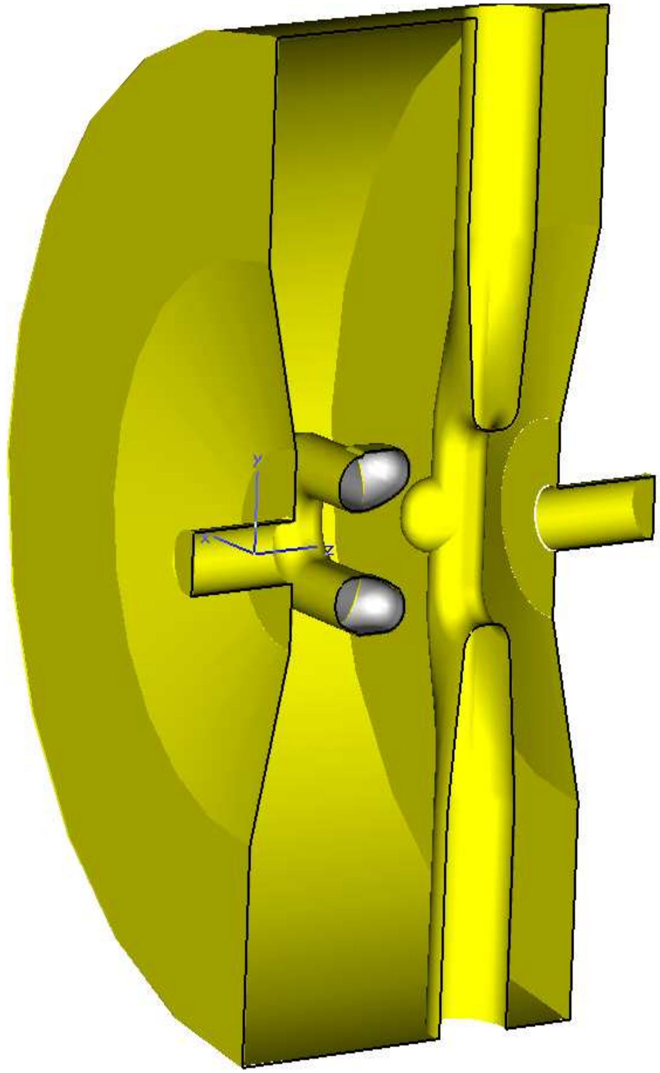
RF-Focusing Gap Geometry

"Finger" protrusions into the accelerating gap produce most of the quadrupole effect.



Focusing strength is controlled by adjusting the size of the finger-like structures.

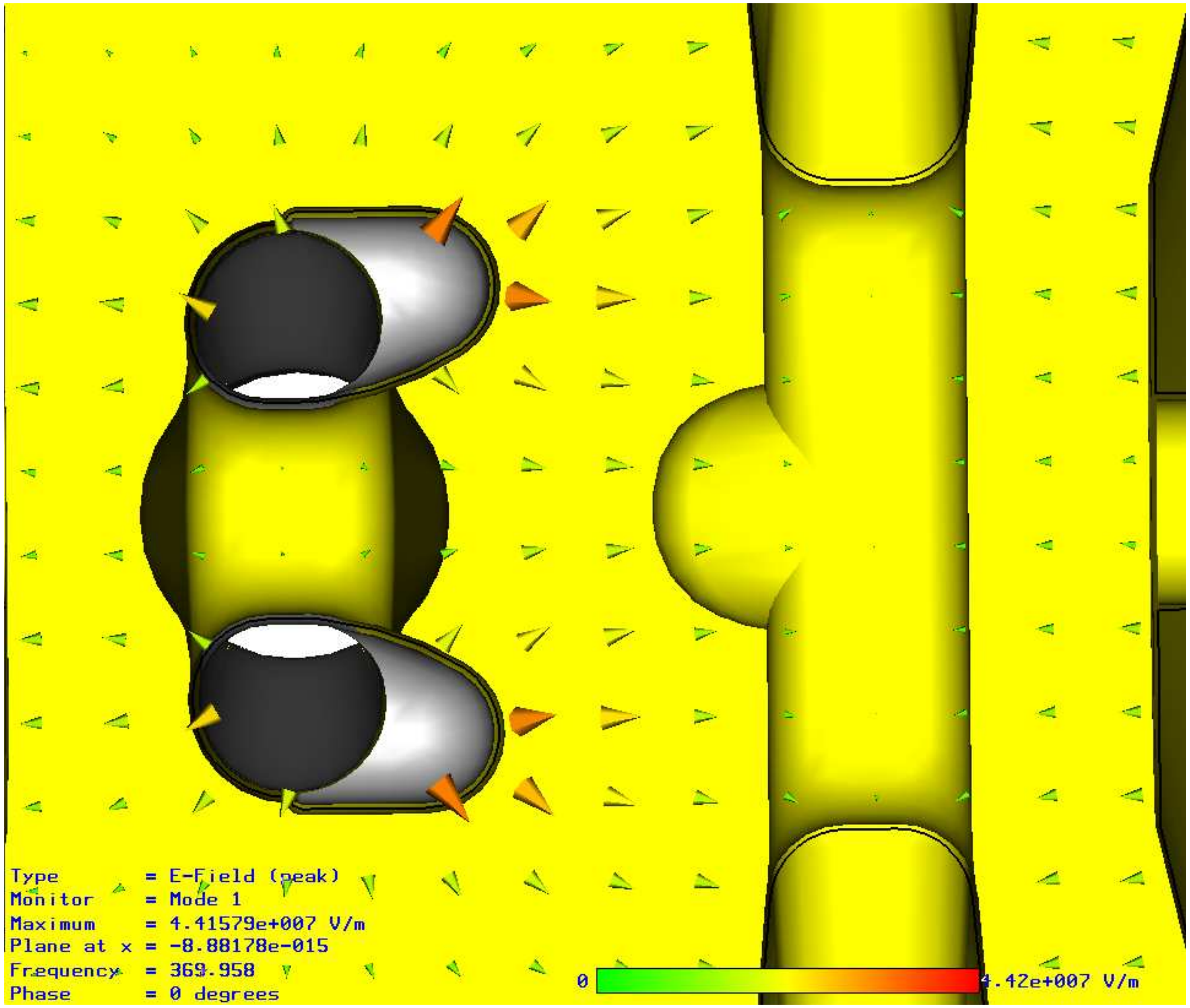
Spoke Cavity Cut-Away View



- 3-Gap Cavity
- Frequency = 350 MHz
- Geometric - β = 0.125

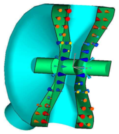
Electric Field – Microwave Studio Results

Accelerating/ Focusing Mode



Cavity Geometry Data
(left end of cavity at 0.0)

Physical length	13.39286 cm	w/o flanges
Center of 1^{st} gap	2.232 cm	short, no quad
Center of 2^{nd} gap	06.843 cm	long, with quad
Center of 3^{rd} gap	11.161 cm	short, no quad
Aperture Radius	1.0 cm	



Microwave Studio Results

Transit-time Factor vs. Proton Beam Velocity

β	*Transit-Time Factor*
0.090	0.5913
0.110	0.7786
0.120	0.7990
0.140	0.7675
0.160	0.6953
0.180	0.6155
0.200	0.5404

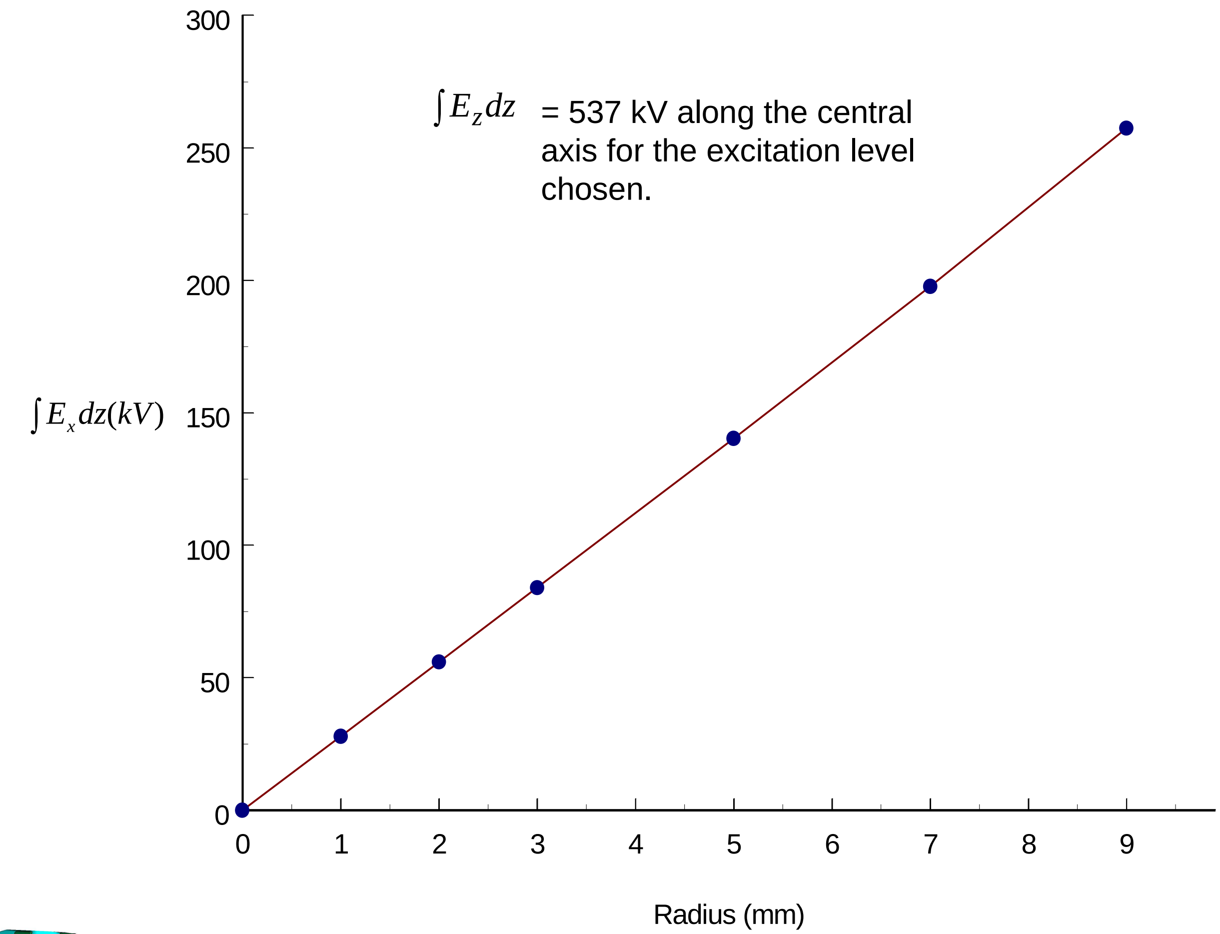
Microwave Studio Results

Cavity RF data

Q_0 *(RT)*	8907
ZT^2 / Q	311 Ω
G	44.69 Ω
Q_0 *(4K)*	7.33E+008
E_p / E_a	14.27
B_p / E_a	170 G/MV/m

Microwave Studio Results -

$\int E_x dz$ as a function of radius



Linear variation indicates good quadrupole.

Some “roll-off” observed at r > 9mm due to weak higher-order spatial modes.

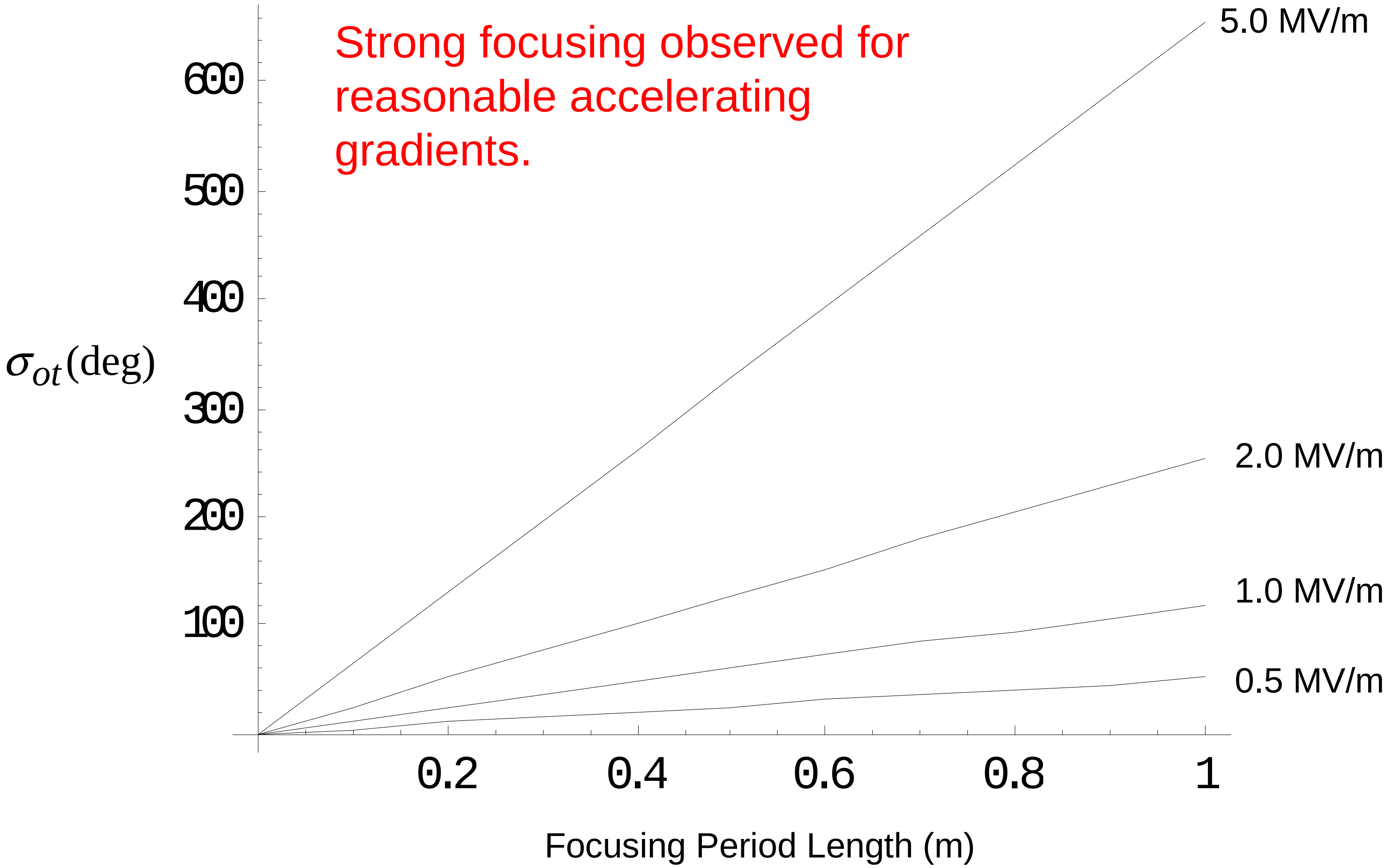
Estimate of Quadrupole Focusing Strength

Zero-current transverse phase advance per unit length in the smooth approximation for singlet electric quadrupole focusing in the spoke cavity:

$$\left(\frac{\sigma_{0t}}{2L}\right)^2 = \left(\frac{e\int E_x dz}{2m\gamma\beta^2 c^2 a}\right)^2 - \frac{\pi e(E_0 T)\sin(-\phi)}{mc^2\lambda\gamma^3\beta^3}$$

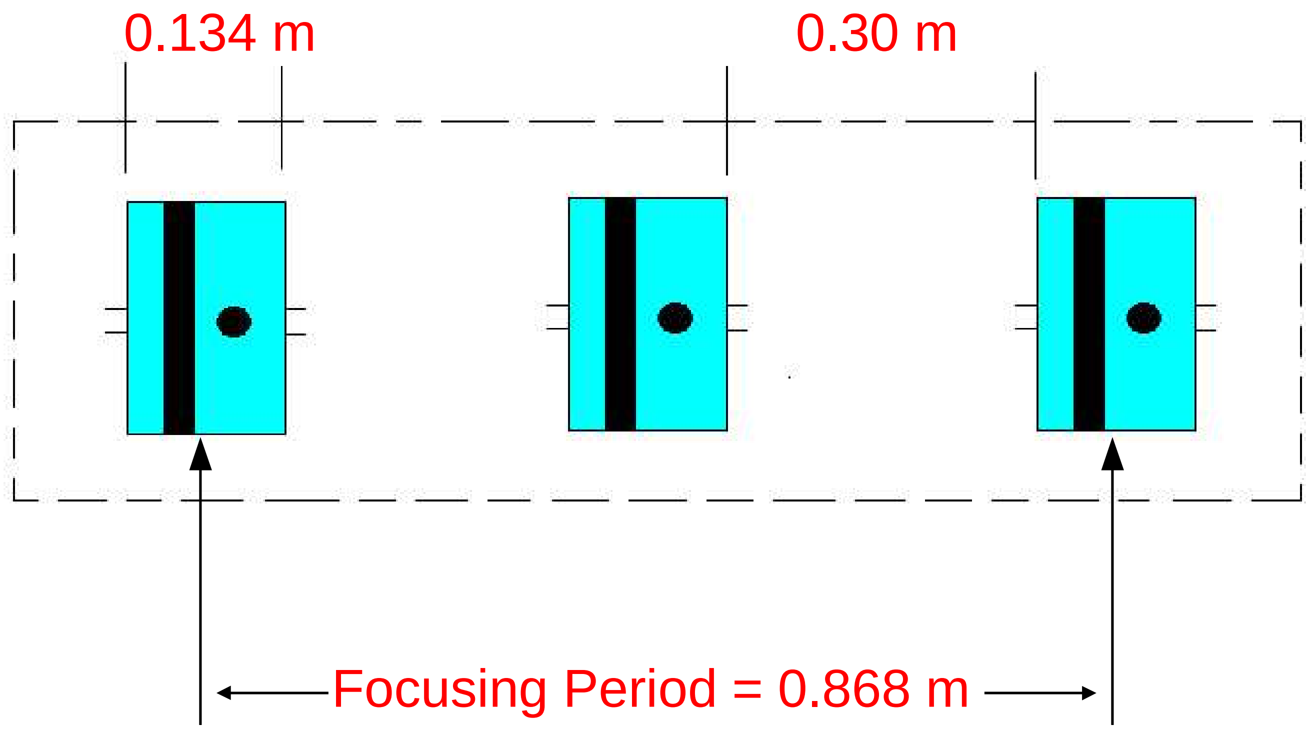
2L " Focusing period length
Ex " Pole-tip electric field
a " Aperture radius
EoT " Axial accelerating gradient
ϕ " Synchronous phase

Transverse phase advance per period vs. period length for various accelerating gradients – 6.7-MeV Beam Energy



Example Focusing Lattice

(assumes short 3-gap 2-spoke cavities)



TRACE 3-D Results – Equivalent Magnetic Quadrupole

Equivalent magnetic quadrupole gradient G:

$$G = \frac{E_x}{\beta ca} \approx \frac{\int E_x dz}{\Delta z} \frac{1}{\beta ca}$$

Δz = gap length of cavity (0.05357 m)

$\int E_x dz$ $\propto$ $E_o T$ and depends on "finger" geometry

TRACE 3-D results for example focusing lattice period (0.868 m), σ_{ot}=80°, and 6.7-MeV beam energy:

Beam Current	Normalized Transverse Emittance (π-cm-mrad)	Transverse Aperture-to-rms Beamsize Ratio
13.3 mA	0.0152	6.6
49.27 mA	0.0183	5.0
94.32 mA	0.0263	3.8

For our cavity geometry, σ_{ot}=80° @ $E_o T$ = 0.691 MV/m

Summary & Issues

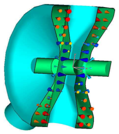
- “Proof of principle” cavity geometry explored using Microwave Studio.
- Cavity shape not yet optimized:

  - Reduce peak surface electric fields further.

  - Examine fraction of surface area at high peak surface fields.

  - Need to study higher-order spatial modes / harmonics.

  - Larger apertures possible?
- Analytical calculations indicate strong focusing possible at low-β.
- This concept shows promise for more compact low-β SC structures – longer multi-gap cavities should be studied.
- Applicable for peak beam currents of order 10 mA for present aperture and lattice using short cavities.
- Transverse and longitudinal beam parameters are coupled – Tuning Issues.
- Cavity prototype required to verify calculations!



References

[1] F. Krawczyk et al., “Design of a Low-β, 2-Gap Spoke Resonator for the AAA Project,” Proceedings of the 2001 Particle Accelerator Conference, Chicago, Illinois, June 18-22, 2001.

[2] P. Lapostolle, Compt. Rend. Vol. 256 (1963), p. 5294-5297.

[3] T. Wangler, “RF Linear Accelerators,” John Wiley & Sons, Inc., 1998, p. 220, equation 7.103.

[4] P. Kelley et al., “ADTF Spoke Cavity Cryomodule Concept,” Los Alamos National Laboratory Report LA-UR-01-3818, July, 2001.

[5] V.V.Vladimirskii, Probory i Tekhn. Eksperim, Vol.3 (1956), p. 35.

[6] J. R. Delayen and K. W. Shepard, “First Tests of a Superconducting RFQ Structure,” Proceedings of the 1990 Linear Accelerator Conference, Albuquerque, New Mexico, September 10-14, 1990, p.76.

Discussion on "RF-Focused Spoke Resonator" by Robert Garnett

The apertures on the spokes are elongated slots, instead of circular holes. This choice was made based on a 2D study by Rick Wood, that showed a cleaner quadrupole characteristics for using this feature.
Garnett pointed out that this concept does couple transverse and longitudinal focusing which removes some flexibility. Shepard answered that one could envision the use of a mix of RF-focus and regular spokes to separate the transverse and longitudinal focusing again. This would remove some of the gained compactness, but still would be more efficient than the use of external focusing elements. A similar concept has been used at TRIUMF, where an extra cavity was injected to provide longitudinal focus.

Closeout Session

All: "*Closeout Discussion*"

(Discussion)

Tom Wangler: "Longitudinal Beam-Dynamics Constraint on the Accelerating Gradient"

(Discussion)

Closeout Discussion

The start of the close-out discussion dealt with multigap spokes. While they are of interest to improve the real-estate gradient of low-β accelerator sections, there is a limit to their usefulness. Very long multi-gap structures do not allow the failure tolerance that is required for applications like RIA or ADS type machines.

Shepard summarized: The advantage of low-β SC structures is that they are short and can be independently driven. Transverse focusing elements can be inserted frequently, which makes them very flexible and useful for high current operation. Proposals for longer structures to reduce cost and increase the real-estate gradient need to show that this advantage is not compromised. No single design will be appropriate for all applications and beam velocities. He acknowledged that the spoke prototypes build and tested by different groups recently, show that cleaning techniques have established these structures as viable candidates for accelerating fields around 10 MV/m. While this demonstrates field wide advantages for spoke resonators in general, detailed implementations, like the number of gaps need to be adapted to the specific application.

Wangler explained that there are limits to the improvement of real-estate gradients for classic separate function beam dynamics (acceleration separated from transverse focusing), especially at low beam velocities. For space-charge dominated beam the longitudinal phase advance per cavity is limited to 90 degrees, else envelope instabilities would be excited. Without space-charge the longitudinal phase advance limit is 180 degrees (Matthew instability). The effect is proportional to β^2, f^{-1} and $1/L^2_{focus}$. This means that the problem increases rapidly with decreasing beam velocity and with increasing focusing length. The frequency dependency is weaker, which makes it worse for proton acceleration than for ion acceleration. On Shepards suggestion more details on this issue have been written up by Tom and are added to these proceedings. Facco confirmed that their designs as based on the limitations described. For very low beam velocities they have a succession of single, short cavities and transverse focusing elements. The beam-dynamics showed that they had to limit the gradient to avoid instabilities. This scheme limits the real-estate gradient. There was general agreement that especially for longer linacs this is not a big hit on the overall efficiency.

Shepard concluded from this that high gradients in a short structure would not be a bad thing in that context, as the focusing length is short. Pierini added that for very high gradients that can be achieved in TESLA class structures Wangler's comments do also hold true.

Bisoffi mentioned that for a recent Legnaro design for a FODO length of 1m 1.2 - 1.3 MV/m real-estate gradient have been achieved. Wangler responded that for AAA up to 12 MeV 0.7 MV/m was the largest stable gradient. Beyond 20 MeV no limitations were seen anymore.

To avoid these instabilities the CH structure with its non-standard focusing concept is very interesting. Sauer mentionend that up to 120 degrees of phase advance per cavity have been achieved.

The final discussion was related to the electromagnetic difference between the CH structure and multigap spoke structures. Sauer listed the girders connecting spoke bases as the major difference. These girders add field stability to these long structures. Zaplatin responded that some of his designs also used these girders and that electromagnetically there was no difference beyond the field stability and the peak surface fields. Thus the only difference seems to be the operational difference in a changing RF-phase between the beginning and the rest of the structure.

The workshop was closed out with two questions: The first suggesting to find a better name than "drifttube structures" for all these loaded (quarterwave, halfwave and spoke structures). No name was suggested. The second question asked if a second of these workshops should be held may be in two years. No volunteers came forward at this point.

Longitudinal Beam-Dynamics Constraint on Accelerating Gradient

T.P.Wangler, Los Alamos National Laboratory

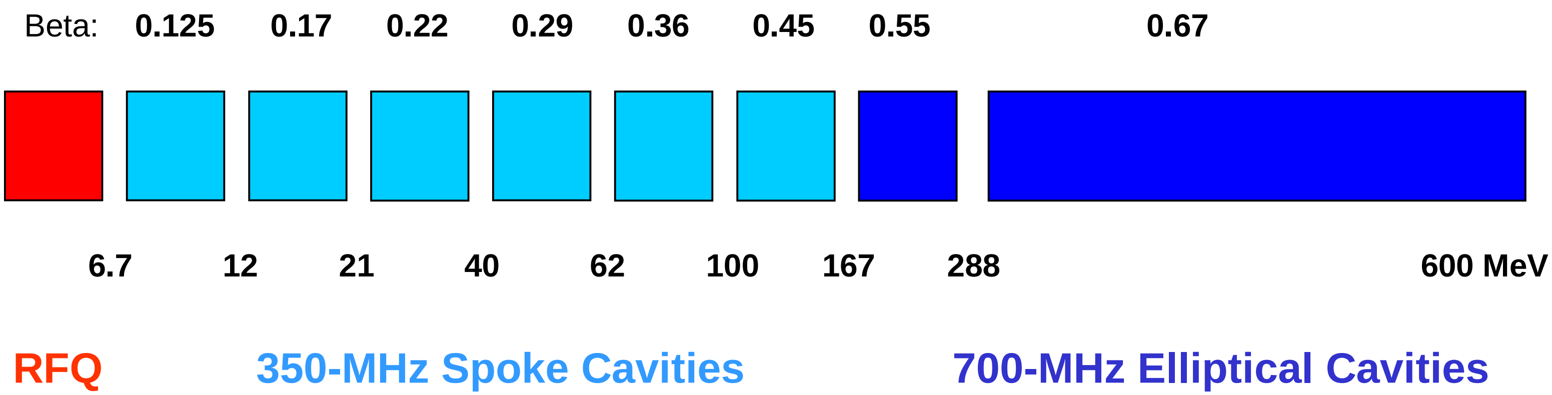
and K.R.Crandall, TechSource

Workshop on Advanced Design of Spoke Resonators

Los Alamos, NM

October 7-8, 2002

High-gradient 20-mA compact CW proton superconducting-linac design for testing of accelerator-driven nuclear waste-transmutation target concepts.



• Our design extended the superconducting linac to much lower velocities all the way down to the RFQ.

• 5-cell spoke cavities were used in first three spoke sections to increase the real-estate accelerating gradient at low beta; 7-cell cavities (spoke and elliptical) were used for entire remaining linac.

• **We found that using high accelerating gradients at low velocities produced the longitudinal envelope instability.**

• Design modifications to be described mitigated the effect and allowed higher gradients to be used.

Longitudinal envelope instability is excited if the accelerating gradient is too large.

- **Longitudinal rms beam size is resonantly driven** (**parametric resonance**) **to larger values by the periodic focusing from rf cavities** when focusing lattice period $L_{period}/\beta c$ is half the period of a mismatch oscillation.

- **Thus, resonance occurs when the longitudinal phase advance per focusing period of longitudinal mismatch oscillation equals 180°.**

Model for longitudinal rms envelope Z in periodic focusing lattice with period L.

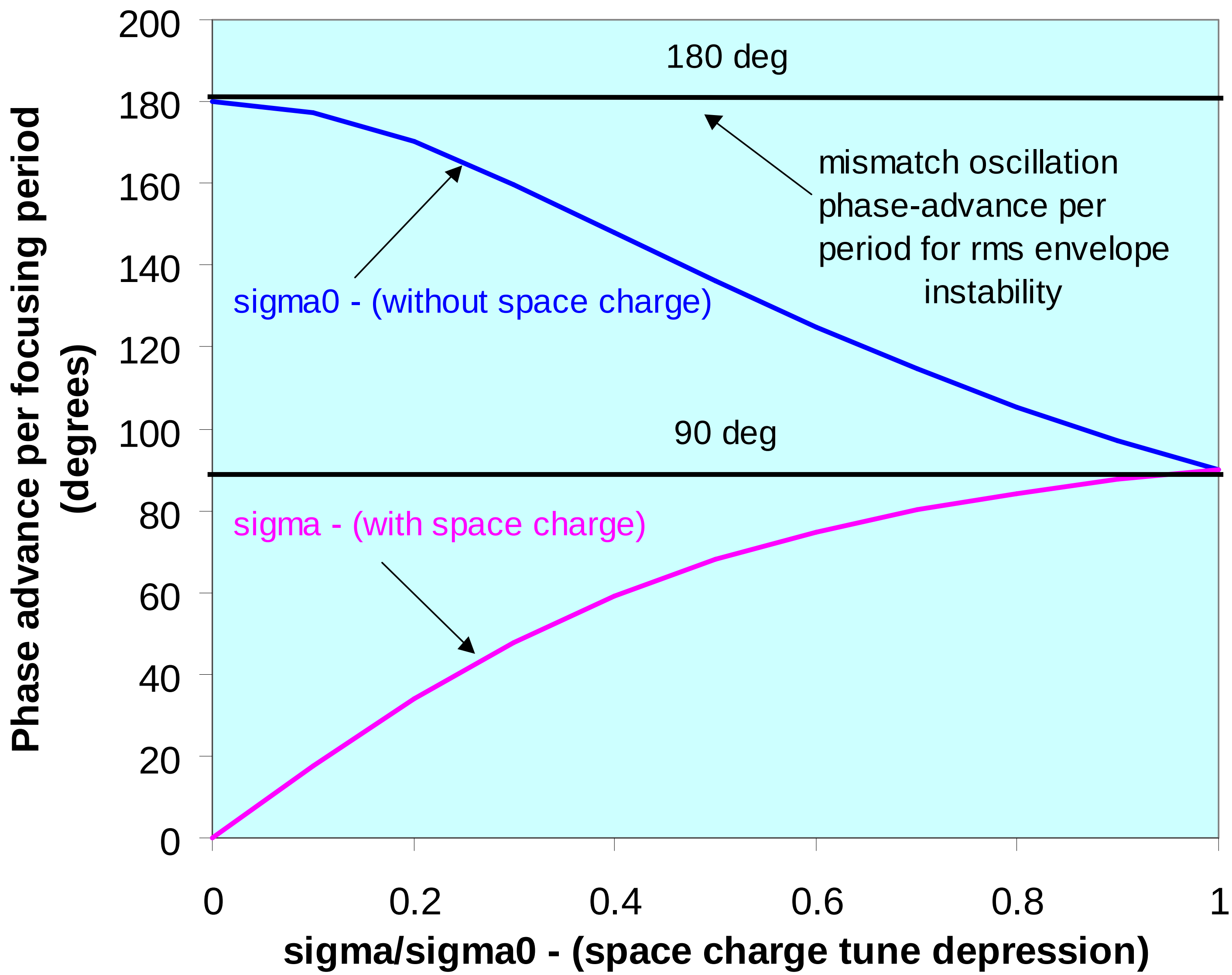
$$Z'' + \left(\frac{\sigma_0}{L}\right)^2 \left(1 + \delta \sin \frac{2\pi s}{L}\right) Z - \frac{\varepsilon^2}{Z^3} - K = 0, \quad \text{longitudinal}.$$

$$\textit{Let } Z = Z_0 + z, \ \textit{for small mismatch } z.$$

$$z'' + \left(\left(\frac{\sigma_0}{L}\right)^2 + \frac{3\varepsilon^2}{Z_0^4}\right) z + \left(\frac{\sigma_0}{L}\right)^2 \delta \sin \frac{2\pi s}{L} z = 0, \quad \textit{parametric resonance}.$$

$$\text{Resonance}: \sigma_{mismatch} = 180°, \ \textit{where} \left(\frac{\sigma_{mismatch}}{L}\right)^2 = \left(\frac{\sigma_0}{L}\right)^2 + \frac{3\varepsilon^2}{Z_0^4}$$

Single Particle Tunes in Smooth Approximation Corresponding to Longitudinal Envelope Instability



We can control σ_0 with external focusing. Safe criterion to avoid envelope instability for all beam currents is $\sigma_0 < 90°$. This limits the average accelerating gradient $\langle E_0 T \rangle$.

$$\left(\frac{\sigma_0}{L}\right)^2 = \frac{2\pi q \langle E_0 T \rangle \sin(-\phi)}{mc^2\gamma^3\beta^3\lambda} \le \left(\frac{\pi}{2L}\right)^2.$$

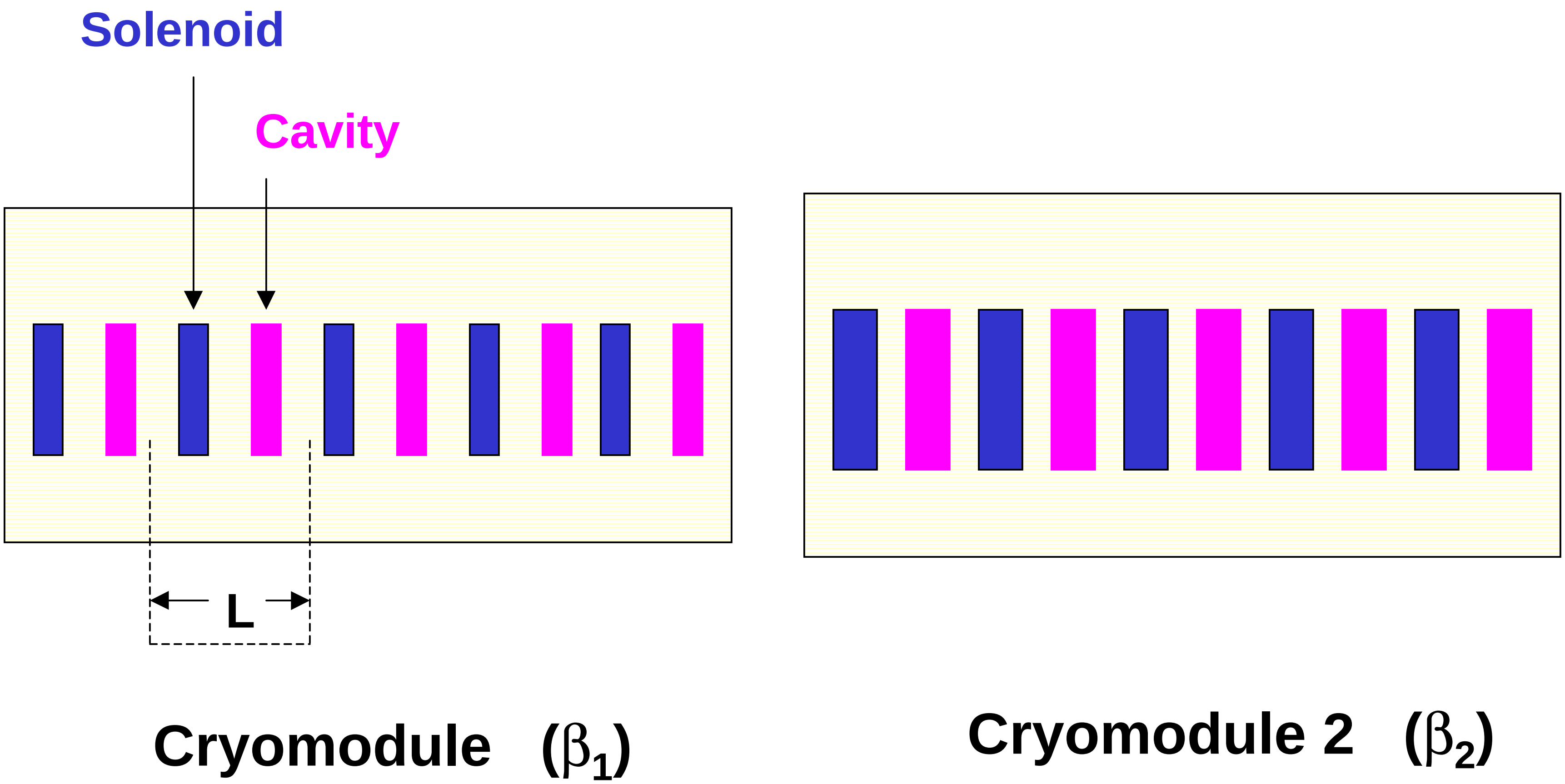
$$\langle E_0 T \rangle \le \frac{\pi mc^2\gamma^3\beta^3\lambda}{8q\sin(-\phi)L_{Period}^2}.$$

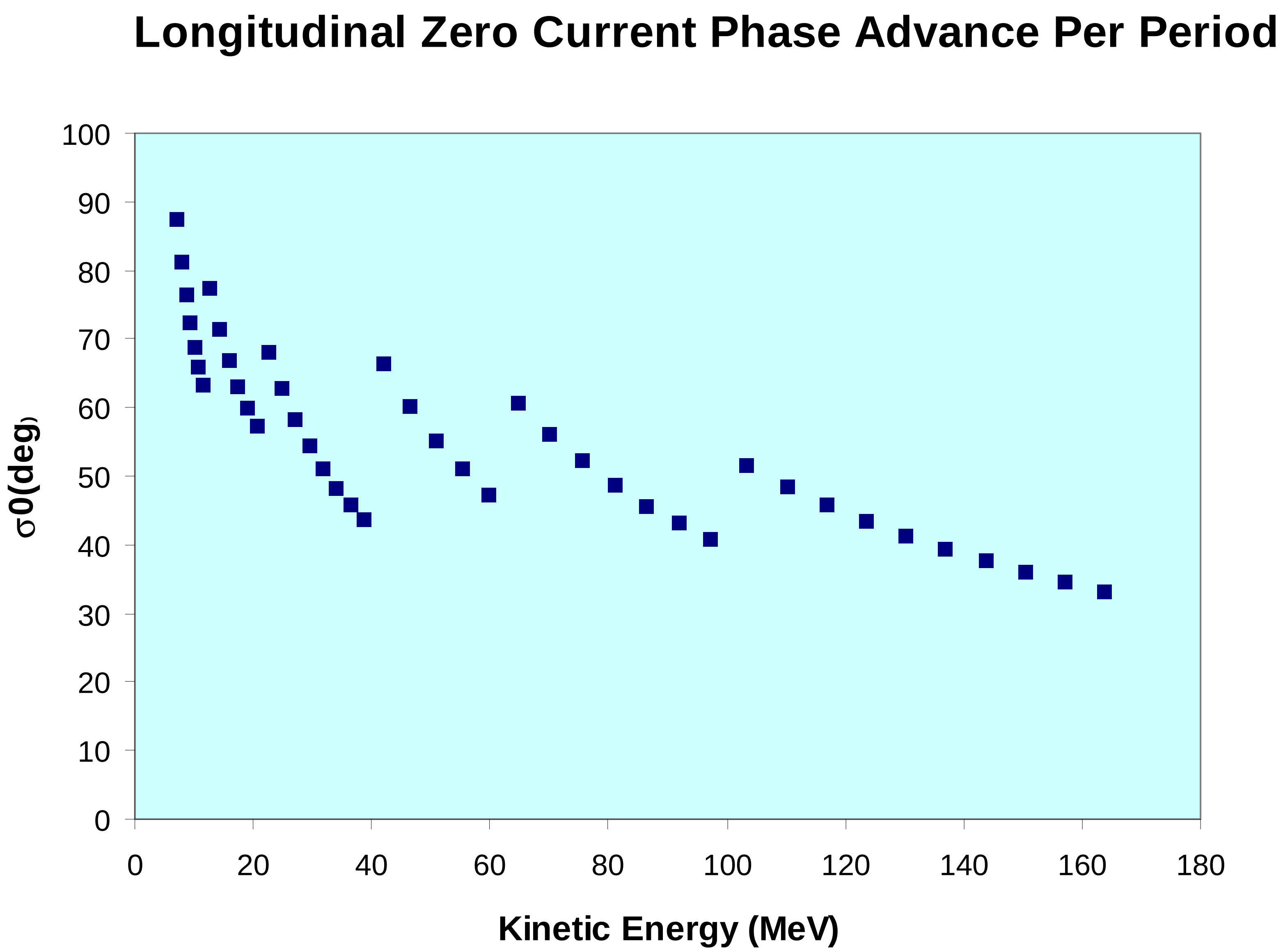
- **The envelope instability constraint is important for high charge-to-mass ratio, low velocities***(cubic dependence)***, high frequencies, and long focusing periods** *(quadratic dependence).*
- **Reducing magnitude of phase ϕ below 30 deg doesn't help because phase width of bucket shrinks causing beam losses.**

A beam-dynamics approach for compact low-velocity proton superconducting linacs

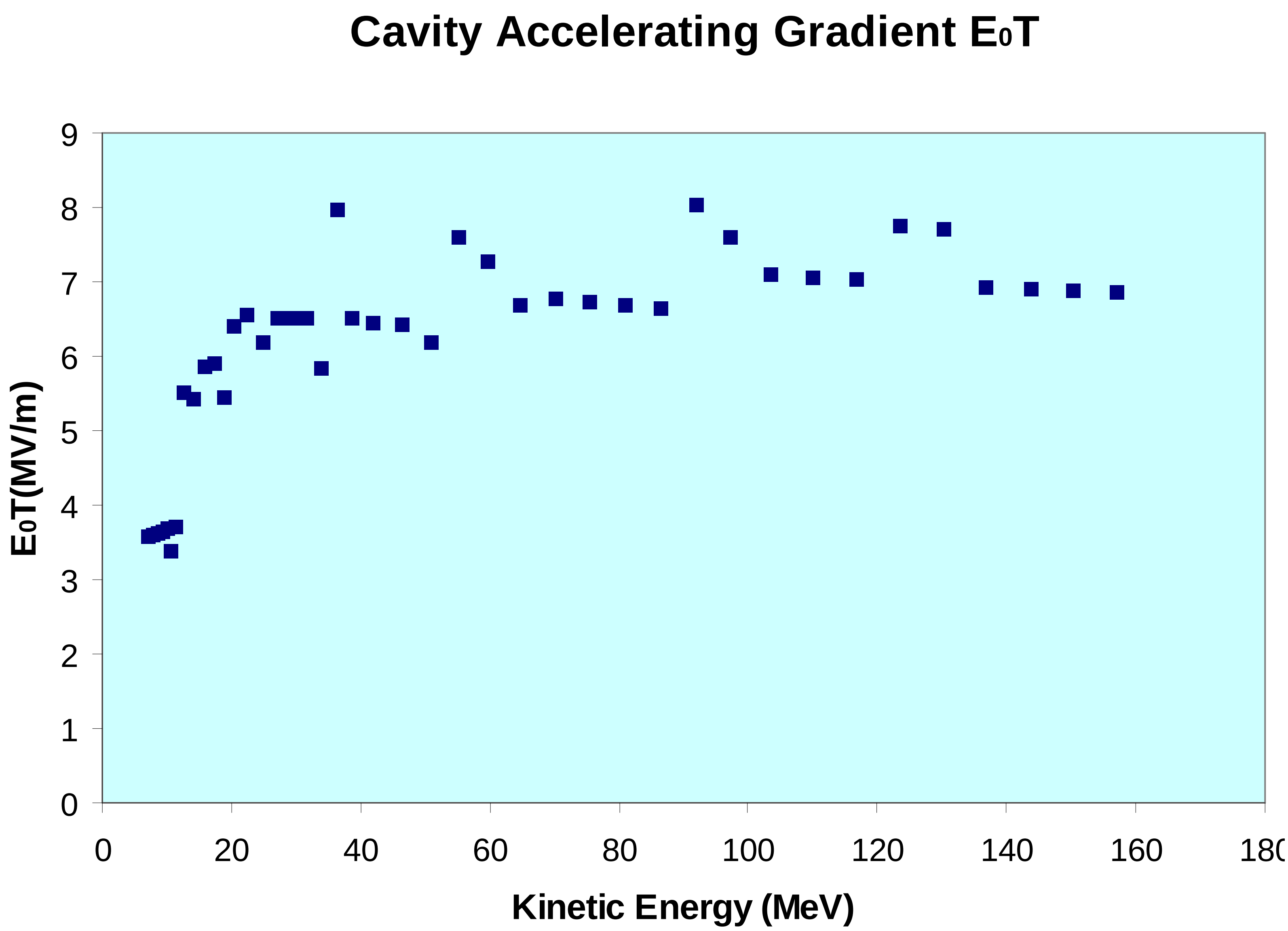
- **Each cryomodule has identical elements and is a short FODO lattice with its characteristic period L.**
- **Allow period to change from one cryomodule to the next.**
  -Do not require that focusing period must be large enough to span the large space between cryomodules.
- **Shorten the focusing period.**
  -Include only one cavity and one solenoid per focusing period.
  -For compactness use solenoids instead of quadrupole multiplets for transverse focusing.
- **Use cavities and solenoids at both ends of cryomodule for matching between cryomodules.**
- **Gradients are still limited by σ_0<90°requirement but these measures help.**

Example of two cryomodules: Cryomodules are short FODO lattices with different focusing periods. Each period consists of one cavity and one solenoid.

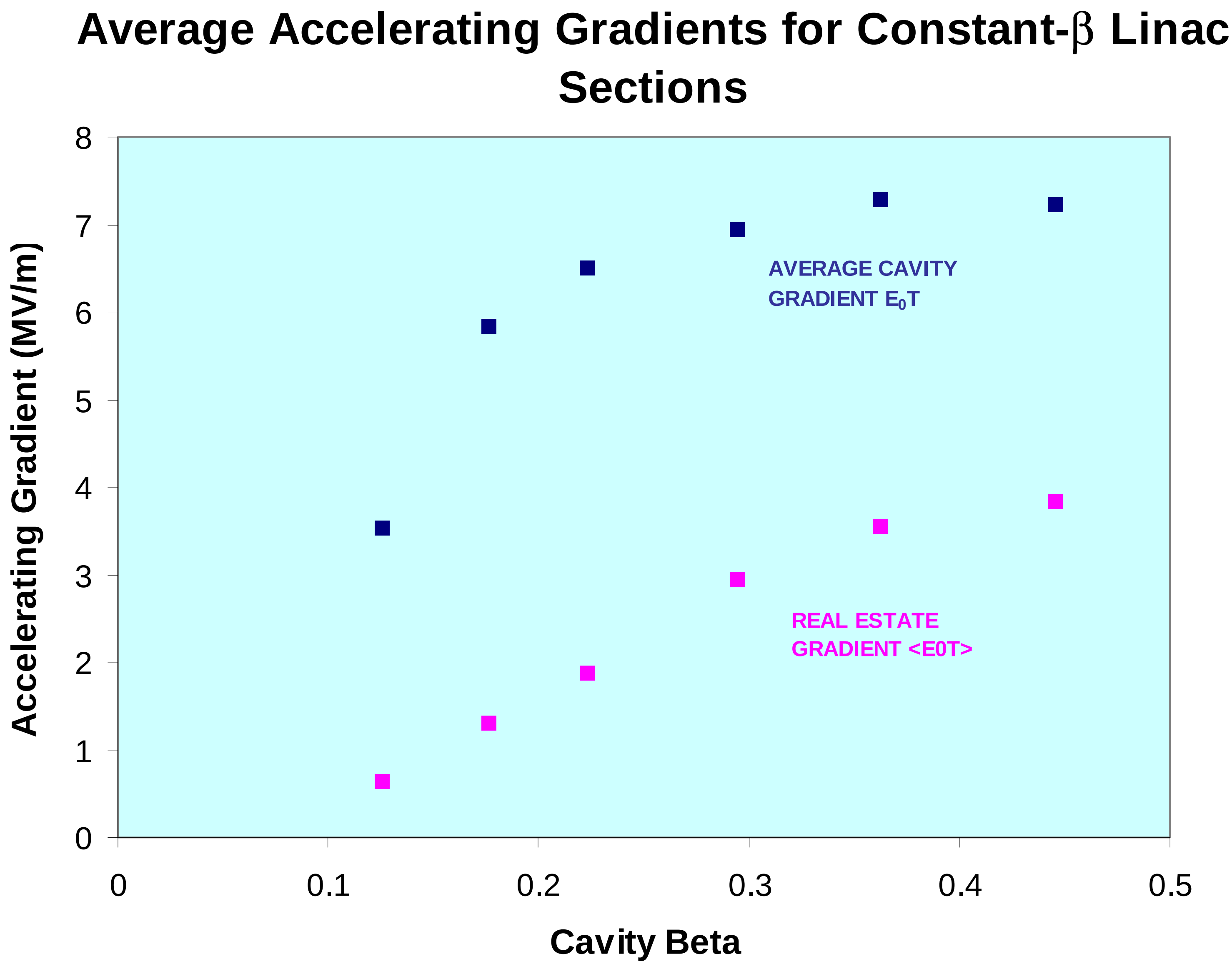




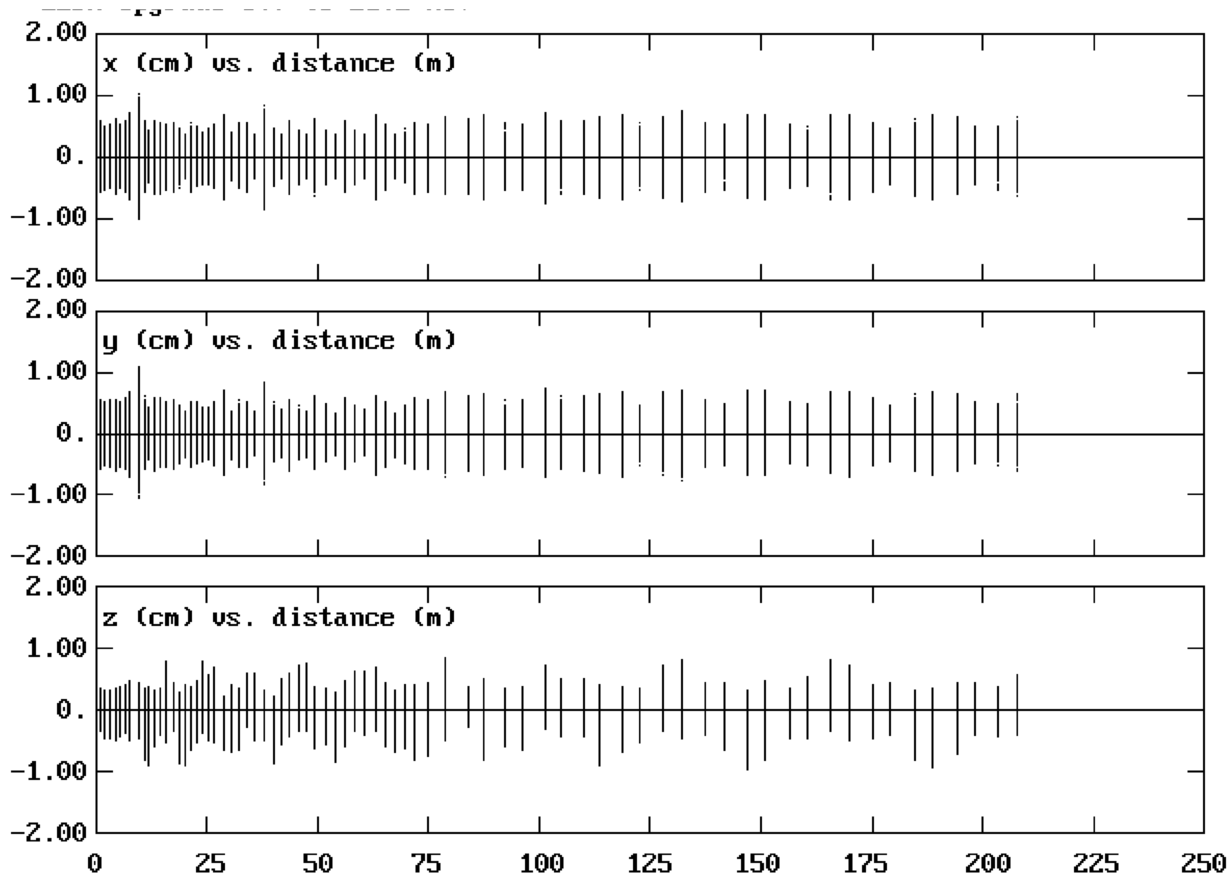
Longitudinal Zero Current Phase Advance Per Period
σ0(deg)
Kinetic Energy (MeV)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160
180



Cavity Accelerating Gradient E0T
E0T(MV/m)
0
1
2
3
4
5
6
7
8
9
0
20
40
60
80
100
120
140
160
180
Kinetic Energy (MeV)


Average Accelerating Gradients for Constant-β Linac Sections
Accelerating Gradient (MV/m)
Cavity Beta
AVERAGE CAVITY GRADIENT E0T
REAL ESTATE GRADIENT <E0T>
0
1
2
3
4
5
6
7
8
0
0.1
0.2
0.3
0.4
0.5

Beam profiles for 8 superconducting sections from 6.7 to 600 MeV after approximate matching between cryomodules. Matching not perfect but satisfactory.



Conclusions

- **The longitudinal envelope instability can limit the accelerating gradient at low-velocities. It is more of a problem for proton (higher frequency and higher q/m) rather than heavy ion superconducting linacs.**

- Our longitudinal beam-dynamics design approach has been to keep σ_0**<90°** and **minimize the focusing period**.

- The cryomodules form piecewise constant FODO lattices where each period contains one cavity and one solenoid.

- For 350-MHz proton linac in β range of **0.2 to 0.5 (20 to 150 MeV)** we could use cavity gradients up to about **8 MV/m** without longitudinal beam-dynamics problems.

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